THE INFLUENCE OF ATMOSPHERIC CONDITIONS ON THE DETECTION OF HOTSPOTS INSIDE A SUBSTATION YARD

by

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Dissertation submitted in fulfilment of the requirements for the degree

MAGISTER: TECHNOLOGIAE:
ENGINEERING: ELECTRICAL

In the

School of Electrical and Computer Systems Engineering

of the

Faculty of Engineering, Information and Communication Technology

At the

Central University of Technology, Free State

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2012-01-01

DECLARATION OF INDEPENDENT WORK

I, Rodney Kleynhans, hereby declare that this research project submitted for the degree MAGISTER TECHNOLOGIAE: ENGINEERING: ELECTRICAL, is my own independent work that has not been submitted before to any institution by me or anyone else as part of any qualification.

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SIGNATURE OF STUDENT DATE

ACKNOWLEDGEMENTS

The successful completion of this dissertation would not have been possible without the advice, support and encouragement of the following:

Prof. Roderick Thomas, his extensive knowledge and experience cannot be expressed in words. His enthusiasm to promote the study of thermograpy knows no boundaries. His willingness to share knowledge, information and documentation helped during my research.

Dr Pierre Hertzog, an accommodating and competent study leader.

Wilhelm Hoffmann, from the Faculty of Natural and Agricultural Science at the University of the Free State for his assistance with the set-up and use of measuring instrumentation, data loggers and programming during the "wind experiment".

Philip Koko, for his assistance in the machines laboratory at the University of Technology, Free State, during the convection experiment.

My wife, Zelna Kleynhans, for her constant encouragement, understanding and support during the research.

Dr J Alleman, from the Faculty of Natural and Agricultural Science, Department Soil, Crop and Climate Science at the University of the Free State, for the use of the controlled environment cabinets for the second and third experiments.

Adriaan Hugo, for the technical specifications for the controlled environment cabinets.

Prof Robbie Brazelle, for his support and assistance from the project proposal to ensuring that a non-specialist in the field of thermography would understand this dissertation.

To the Lord, through Whom all is possible and for giving me the ability and strength to complete this study.

Summary

Infrared thermography is a non-contact method of identifying the thermal behaviour of various plant equipment and machines, including their components, qualitatively via pattern recognition and quantitatively via statistical analysis. This allows for the development of condition monitoring and predictive failure analysis. It is well established that optimized maintenance planning can be more effective when a problem is detected in the early stages of failure. For example, in electrical systems an elevated electrical resistance caused by loose or corroded connections, broken conductor strands and dirty contact surfaces, results in localized heating, and a unique infrared pattern when analysed leads to the location of the problem and an indication of its severity.

In recent years industrial thermography has used infrared detectors in the long wave portion of the electromagnetic spectrum normally between 8µm and 15µm, due partly to the fact that these wavelengths are not susceptible to solar radiation and/or solar glint.

A number of scientific experiments were carried out on test apparatus to improve the understanding of the impact of convection, ambient air temperature and relative humidity on resultant infrared thermal images. Two similar heat sources, simulating a hotspot, at different temperature settings were used to determine whether the hotspot temperature should also be considered in conjunction with the atmospheric elements. The need for these experiments has also been identified by EPRI (Electrical Power Research Institute) in the USA as necessary to develop international severity criteria, and it is hoped that this study will contribute to this goal.

The accuracy of infrared thermography can be affected by various environmental conditions. This is particularly concerning when establishing severity criteria as in reporting and alarm settings.

Just as wind cools down one’s skin when exposed, it also cools down a hotspot on electrical systems, especially those brought about by I^2R losses. To better understand the effect of wind and how it will influence the thermal image, it is important to know and understand the composition of atmospheric elements, how they react in nature and what influences them. It is also important to distinguish between measured temperatures and energy and if there is any relationship between them.

When the heat sources are exposed to the same wind conditions for the same time period, it was found that at lower heat source temperatures there is less energy available, resulting in more heat being lost by a hotspot exposed to windy conditions than by a hotspot of higher temperature. Less energy means less resistance to retaining its temperature. During this test a 29% temperature loss was measured for the heat source with the higher initial temperature and 35% for the heat source with a lower initial temperature, with an average wind of 28.18km/h over a 10 minute exposure period. Due to this phenomenon, faults in the early stages might be overlooked when performing thermal inspections on a windy day. The inverse is true for energy loss as opposed to temperature loss. The more energy the heat source has to start off, the more it is prone to lose it to the environment.

When the heat sources are exposed to the same air conditions for the same time period, the heat source with the lower initial temperature, i.e. less severe problem, was influenced more by the air temperature. The rate of heat transfer is dependent on the temperature difference between two objects. This means that the rate of heat transfer will change with a change in air temperature or heat source temperature. When the air temperature was increased, the measured temperature of the heat sources decreased. This is due to the energy transfer between the surroundings and the heated object. The first law of thermodynamics states that in a closed system, the energy entering the system equals the energy leaving the system [7, p. 516]. The increased energy of the surrounding air must be transferred from somewhere, and the somewhere in the case of this experiment is the heat source.

At low ambient air temperatures, a higher radiated heat source temperature was measured for both heat source X and heat source Y than at higher air temperatures. Again the lower quantity of available energy results in a lower resistance to retain its temperature. A hotspot measured at lower air temperatures would be more severe than one with the same temperature at higher air temperatures. Lower hotspot temperatures would also be influenced much more easily by the air temperatures than would hotter hotspots. The rate at which the change occurs is neither uniform nor predictable. The percentage of measured temperature loss calculated between air temperature settings during the experiment, varied between 1.71% and 3.14% for the heat source with the higher initial temperature, and 3.68% and 5.02% for the heat source with the lower initial temperature.

Relative humidity is dependent on the air temperatures. Higher air temperatures result in an increase in the kinetic energy of molecules, increasing the rate of evaporation. This happens in nature on a daily basis. Mornings with low air temperatures have less energy resulting in high relative humidity, whereas warmer afternoons have more energy resulting in lower relative humidity. Although the influence of changing relative humidity on a hotspot is extremely small, the heat source with the lower initial temperature, i.e. a less severe problem, was influenced more by the changing relative humidity. At low relative humidity, low energy of the air, the lower quantity of available energy of the heat source results in a lower resistance to retaining its temperature. At high relative humidity, high energy of the air, the lower quantity of available energy of the heat source results in a lower resistance to counter the energy transfer as the molecules fall onto the surface of the heat source, transferring some of the energy of the air to the heat source. This results in a slightly higher measured temperature of the heat source. Heat source X lost 0.02% of its temperature to the surrounding air at a relative humidity of 50.2%, but gained 0.12% at a relative humidity of 63.8%. Heat source Y lost 0.16% of its temperature to the surrounding air at a relative humidity of 50.2%, but gained 0.93% at a relative humidity of 63.8%.

Opsomming

Infrarooi skandering is ‘n nie-tasbare metode om die termiese eienskappe van verskeie masjienerie en toerusting, insluitende hul komponente, te identifiseer. Dit kan kwalitatief, deur patroon herkenning of kwantitatief, deur statistiese analise gedoen word. Dit lei tot die ontwikkeling van kondisie-monitering asook voorkomende analise. Dit is alombekend dat optimale onderhoudsbeplanning meer effektief is wanneer ‘n probleem in die beginstadium geïdentifiseer en herstel word. In ‘n elektriese sisteem byvoorbeeld, sal ‘n verhoging in elektriese weerstand wat veroorsaak word deur los, geoksideerde, gebreekte geleierdrade, of vuil kontakoppervlaktes, aanleiding gee tot gelokaliseerde hitte, met ‘n unieke infrarooi patroon. By nadere ondersoek kan dit lei tot die opsporing van die probleem en ‘n aanduiding van die graad van erns van die problem weergee.

Tans maak industriële infrarooi-skandering gebruik van lang-golf infrarooi-skandeerders van die elektomagnetiese spektrum, normaalweg tusssen 8µm en 15µm. Dié gedeelte van die elektromagnetiese spektrum word minder beïnvloed deur son uitstraling.

‘n Aantal wetenskaplike eksperimente is gedoen op toetsapparate om die impak van konveksie, lug temperatuur en relatiewe humiditeit op die resultate van infrarooi-skandering beter te verstaan. Twee hittebronne, elk met sy eie temperatuur, is gebruik sodat bepaal kon word of die temperatuur van die oorverhitte komponent asook atmosferiese komponente in gedagte gehou moet word wanneer foute opgespoor word met behulp van ‘n infrarooi-skandeerder. Die behoefte aan soortgelyke eksperimente is reeds deur die EPRI (Electrical Power Research Institute) in die VSA geïdentifiseer om sodoende internasionale probleemkriteria daar te stel. Deur hierdie studie word gepoog om ‘n bydrae te lewer ten opsigte van die identifisering van probleemkriteria.

Die akkuraatheid van infrarooi-skandering kan beïnvloed word deur verskeie omgewingselemente. Dit is veral kommerwekkend as gekyk word na die erns van rapportering met betrekking tot alarmopstellings.

Wind koel die menslike liggaam af as die liggaam daaraan blootgestel word. Soortgelyke verkoeling vind plaas wat betref ‘n warmbron in ‘n elektiese sisteem, veral die wat ontstaan as gevolg van I^2R verliese. Om die invloed van die omgewingselemente beter te begryp, is dit belangrik om die samestelling van atmosferiese elemente te verstaan, asook hoe dit reageer en wat dit beïnvloed. Dit is ook nodig om te kan onderskei tussen temperatuur en hitte-energie en wat die verwantskap tussen dié twee is.

Wanneer die hittebronne blootgestel word aan dieselfde windkondisies vir dieselfde periode, is gevind dat die koeler bron van die twee meer temperatuur verloor as die warmer bron. Dit is as gevolg van die kleiner hitte-energie wat die koeler bron besit. Die minder beskikbare energie verhinder die hittebron om sy temperatuur te behou en die bron verloor dit gevolglik aan die omgewing. Gedurende die eksperiment is gevind dat daar 29% temperatuurverlies was by die warmer hittebron en 35% temperatuurverlies by die koeler bron toe dit blootgestel is aan ‘n gemiddelde wind van 28.18km/h vir 10 minute. As gevolg hiervan kan foute in die beginstadium oorgesien of beskou word as minder ernstig wanneer daar in winderige toestande infrarooi-skandering gedoen word. Die omgekeerde is waar vir energieverlies teenoor temperatuurverlies. Hoe meer energie beskikbaar is, hoe meer energie word deur die bron verloor aan die omgewing.

Wanneer die hittebronne blootgestel word aan dieselfde lugtemperatuur vir dieselfde tydsperiode is gevind dat die koeler hittebron meer beïnvloed word deur die lugtemperatuur as die warmer hittebron. Die tempo van hitte oordrag is afhanklik van die temperatuur verskil tussen twee voorwerpe. Dit beteken dat die tempo van hitteoordrag sal verander as óf die lug temperatuur óf die hittebron temperatuur verander. Wanneer die lugtemperatuur verhoog word, word ‘n laer hittebrontemperatuur gemeet. Dit is as gevolg van die energieoordrag tussen die lug en die hittebron. Die eerste wet van termodinamika bepaal dat in ‘n geslote stelsel; energie wat die stelsel inkom is gelyk aan die energie wat die stelsel verlaat. Die verhoging in energie van die lug moet iewers heen oorgedra word. In die geval van die eksperiment is dit die hittebron. Vir beide hittebron X en hittebron Y is ‘n hoër hittebron temperatuur gemeet by laer lugtemperatuur as by hoër lugtemperature. Minder energie beteken minder weerstand om die bron se oorspronklike temperatuur te handhaaf. Wannneer ‘n hittekol opgespoor word op ‘n koel dag, is dit meer ernstig as ‘n hittekol van dieselfde temperatuur, op ‘n warm dag met dieselfde las. Laer warmkoltemperature word makliker beïnvloed deur lugtemperatuur as warmer hittekolle. Die spoed waarteen die verandering gebeur is nie uniform of voorspelbaar nie. Die persentasie temperatuurverlies bereken tussen die lugtemperatuurverstellings gedurende die eksperiment het gewissel tussen 1.71% en 3.14% vir die warmer hittebron, en 3.68% en 5.02% vir die koeler hittebron.

Relatiewe humiditeit is afhanklik van die lugtemperatuur. Hoër lugtemperature veroorsaak ‘n verhoging in die kinetiese energie van molukules wat verdamping ook laat verhoog. Bogenoemde kom daagliks in die natuur voor. Oggende met ‘n lae lugtemperatuur het minder energie wat lei tot ‘n hoë relatiewe humiditeit, terwyl warmer middae meer energie het wat lei tot laer relatiewe humiditeit. Alhoewel die invloed van veranderende relatiewe humiditeit op ‘n hittebron baie klein is, word die hittebron met die laer aanvanklike temperatuur meer beinvloed deur die veranderende relatiewe humiditeit.

Lae relatiewe humiditeit en minder energie van die hittebron beteken minder weerstand om die bron se oorspronklike temperatuur te behou. Die omgekeerde gebeur egter by hoë relatiewe humiditeit waar die lae energie van die hittebron te klein is om die “inval” van molekules tee te staan en op die manier baie min energie oordra van die lug na die hittebron. Die resultaat is ‘n effens hoër hittebrontemperatuur. Hittebron X het 0.02% temperatuur verloor by ‘n relatiewe humiditeit van 50.2%, maar het ‘n 0.12% verhoging in temperatuur by relatiewe humiditeit van 63.8% getoon. Hittebron Y het 0.16% temperatuur verloor by ‘n relatiewe humiditeit van 50.2%, maar het ‘n 0.93% verhoging in temperatuur by ‘n relatiewe humiditeit van 63.8% getoon.

List of acronyms

AC - Alternating current

Av. - Average

BS – British standard

EPRI - Electrical Power Research Institute

FOV - Field of view

Ge – Germanium

HgCdTe - Mercury cadmium telluride

Hz - Hertz

IFOV - Instantaneous field of view

IFOVmeas - Measurements instantaneous field of view

IMV - International Meteorological Vocabulary

InSb - Indium antimonite

IRFPA - Infrared focal plane array

ISO – International standard organisation

LCD - Liquid crystal display

MRDT - Minimum resolved temperature difference

NETD - Noise equivalent temperature difference

PBL - Planetary boundary layer

PtSi - Platinum Silicade

RH - Relative humidity

Si - Silicon

ZnSe - Zinc Selenide

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Chapter 1

1.1 Introduction

Infrared thermography is the study of temperature variations through infrared-sensitive equipment. The application of infrared thermography spreads into many fields including electrical, mechanical, construction, aeronautics and medical, to name but a few. Thermography aids in locating and predicating potential problems pertaining to heat loss or heat distribution. Temperature is a key condition indicator associated with deterioration of equipment. For example, a number of conditions in an electrical system can affect the life of the system, namely localized overheating. The magnitude of this problem may be calculated by Joule's law in that a small change in resistance will result in a doubling of current. The severity of a hotspot is determined by the temperature difference of adjacent equipment of the same phase. The temperature of the hotspot is directly proportional to the resistance of the equipment as well as the current. Another important factor besides electrical load that needs to be considered when taking temperature measurements with a thermal imager, is the object's emissivity. Emissivity refers to the ability of material to radiate energy from its surface by comparing it to a blackbody, which is a perfect radiator at the same temperature.

Depending on the use, thermography may be qualitative or quantitative. Qualitative refers to heat patterns which are examined and analysed, and quantitative refers to radiometric temperature measurements, where the differences in near exact temperatures are used to determine the severity of the problem by means of statistical analysis.

Objects emit, reflect or transmit electromagnetic radiation of a wavelength depending on the object's temperature. Kirchhoff quantified how photons react when they interact with a surface.

$$R + A + T = 1 \qquad (1.1)$$

Where:

R = Reflection

A = Absorption or emitted

T = Transmitted

Figure 1.1 illustrates the interaction of radiation on a surface with regard to absorption, reflection and transmitted through the surface.

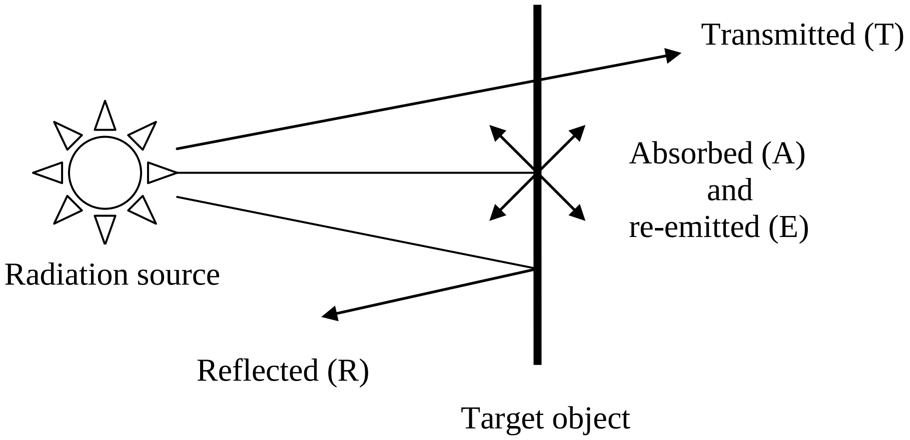


Figure 1.1 Interaction of radiation on a surface

Other factors that influence accurate radiometric temperature measurements relate to the object’s surroundings. These include the following:

- Wind (convection) – speed, direction and temperature
- Moisture – condensation (humidity) and amount (rain)
- Solar load – How long it was exposed to the sun
- Solar reflection
- Surface conditions of the object – is it polished or rusted

1.2 Aim of the study

The aim of this study is to prove that wind, air temperature and relative humidity have an influence on the temperature readings obtained with a thermal imager of a hotspot. These findings would be useful in accurately determining the severity of problems detected in various environmental conditions. It will also be determined whether the temperature of the hotspot (problem area) also influences the percentage of heat loss and percentage of energy loss to the object or across a surface of the object when exposed to the same environmental conditions for the same time period.

1.3 Hypothesis

When investigating a hotspot, wind will have a cooling effect on the hotspot irrespective of its temperature. The temperature and energy loss will be proportional to the wind speed (convection). The rate at which temperature changes, is proportional to the rate at which heat is transferred [5]. The degree of temperature and energy loss should thus be the same for a hotspot at 400°C and 200°C. Due to heat transfer, air temperature and relative humidity will also have a cooling effect on a hotspot, but less than convection. The same rules should then apply for hotter and colder objects exposed to air temperature and relative humidity as opposed to convection. Energy transfer would be greater at lower air temperatures than at higher air temperatures [17]. This is due to the law of conservation of energy.

1.4 Project flow

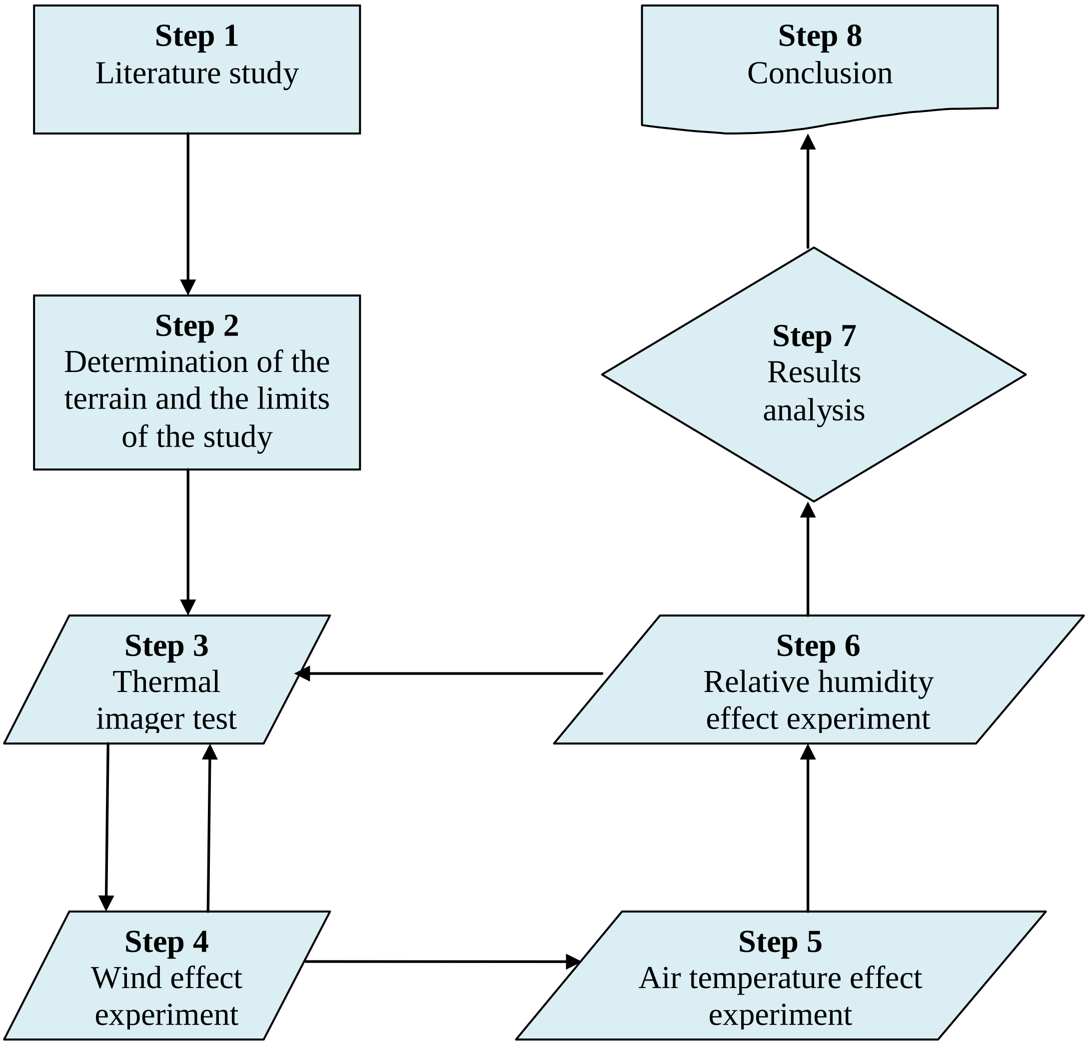


Figure 1.2 Flowchart depicting the thermographic research process

Chapter 2

Climatic Elements

2.1 Introduction

Weather and climate play a very important role in our daily lives. Due to its unpredictable nature, we have all waited for the evening weather report to see what the weather will hold for the next day. Will it be hot or will it be cold? Will it rain or will the wind blow you off your feet? Farmers and thermographers doing outside work, are more dependent on the weather than city dwellers working in office buildings. Farmers wait for favourable conditions to start preparing and plant their fields while thermographers use the weather report to plan trips and schedule outside inspections.

To a thermographer it is important to know how strong the wind will blow (velocity), whether it will rain and how hot will it be (air temperature). These conditions may change his/her decision to do outside thermal inspections on that particular day. Although there is no correction factor for wind, knowing the wind speed and the load when detecting a hotspot will assist the thermographer to better categorize the severity of the problem found. Not knowing the effect of atmospheric conditions may lead to catastrophic end results, such as incorrect analysis of the problem and its severity. Previous studies have shown that wind plays a major role in the masking of hotspots and that ambient air temperature and relative humidity should also be taken into account but do not explain to which extent [17]. The questions that will be answered during this research will be:

1. To what extent do climatic elements influence hotspot detection?

2. Should the temperature of the hotspot be considered when reporting on these problems?
3. Does each climatic element contribute separately or is it a mixture of all of them? and
4. Hypothetically, will wind on its own have the greatest effect, followed by ambient temperature and relative humidity?

Wind combined with a high relative humidity will have a greater cooling effect on the hotspot than a wind with a low relative humidity. This is due to evaporation and convective cooling [17].

According to the International Meteorological Vocabulary (IMV), a climatic element is any one of the properties or conditions of the atmosphere which together specify the physical state of the weather or climate at a given place for any particular moment or period of time [19]. Examples of climatic elements thus include dry-bulb temperature, wet-bulb temperature, wind speed and direction, cloud cover, visibility, sunshine duration and atmospheric humidity.

For the purpose of this study the focus is on the following three elements that may influence thermgraphy results:

- air temperature,
- wind and
- water vapour (relative humidity).

2.2 Temperature

Whereas heat is a measure of the total kinetic energy (movement) of molecular motion and is thus directly proportional to the mass of air being considered, temperature is a measure of the average kinetic energy of molecular motion and is thus independent of mass [25, p. 1]. Temperature can be measured above the absolute zero on the Kelvin scale or on the Celsius or Fahrenheit scales. The relationships between these scales are expressed in the following conversion equations:

To convert:

$$K = 273 + {}^{\circ}C \tag{2.1}$$

$$^{\circ}C = (^{\circ}F - 32) \div 1.8 \tag{2.2}$$

$$^{\circ}F = (^{\circ}C \text{ x } 1.8) + 32 \tag{2.3}$$

Where:

°C = Celsius temperature scale

K = Kelvin temperature scale

°F= Fahrenheit temperature scale

The second law of thermodynamics asserts that, in a closed system, the net flow of heat energy is always from warmer to cooler regions, unless work is done to move it in the other direction. There are three mechanisms for transferring heat:

- Conduction – heat energy is transferred by collisions of heat-carrying molecules.
- Convection – involves the bodily movement of the more energetic molecules in a liquid or gas, e.g. air.
- Radiation – involves the flow of electrometric radiation [25, p. 3].

2.2.1 Atmospheric structure

The atmosphere is not uniform but has significant variations in temperature and pressure with altitude. The atmosphere has a series of distinct layers with distinct temperature gradients. In the lowest of these layers the troposphere temperature decreases with an increase in altitude as can be seen from figure 2.1. This is due to the number of air molecules that decrease with height. The heating of the lower stratosphere is caused by absorption of high-energy ultraviolet radiation by ozone [21, pp. 47-49].

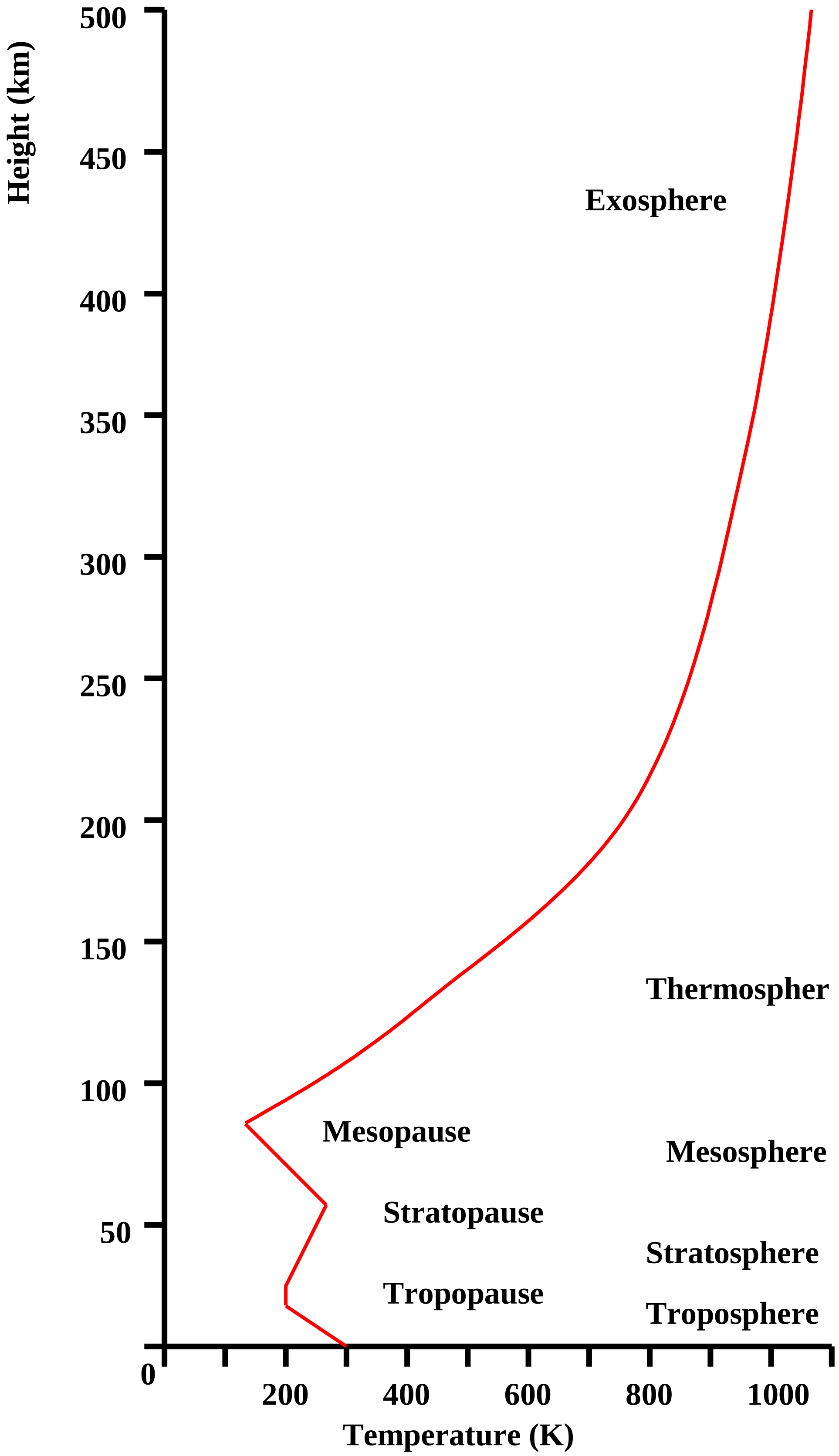


Figure 2.1 Temperature variations with height in the atmosphere [21, pp. 47-49]

Figure 2.2 shows the relationship between atmospheric and soil temperature relative to its height [4, p. 10]. Commencing soon after sunrise the heating of the ground causes a steep unstable lapse rate in the lower air layers. This persists and deepens throughout the morning and early afternoon. Once surface cooling is established after sunset, the lapse rate in the lowest layers is reversed. During the night this layer of reversed lapse rate deepens, only to be replaced by more normal conditions as the cycle starts again after dawn [4, p. 10].

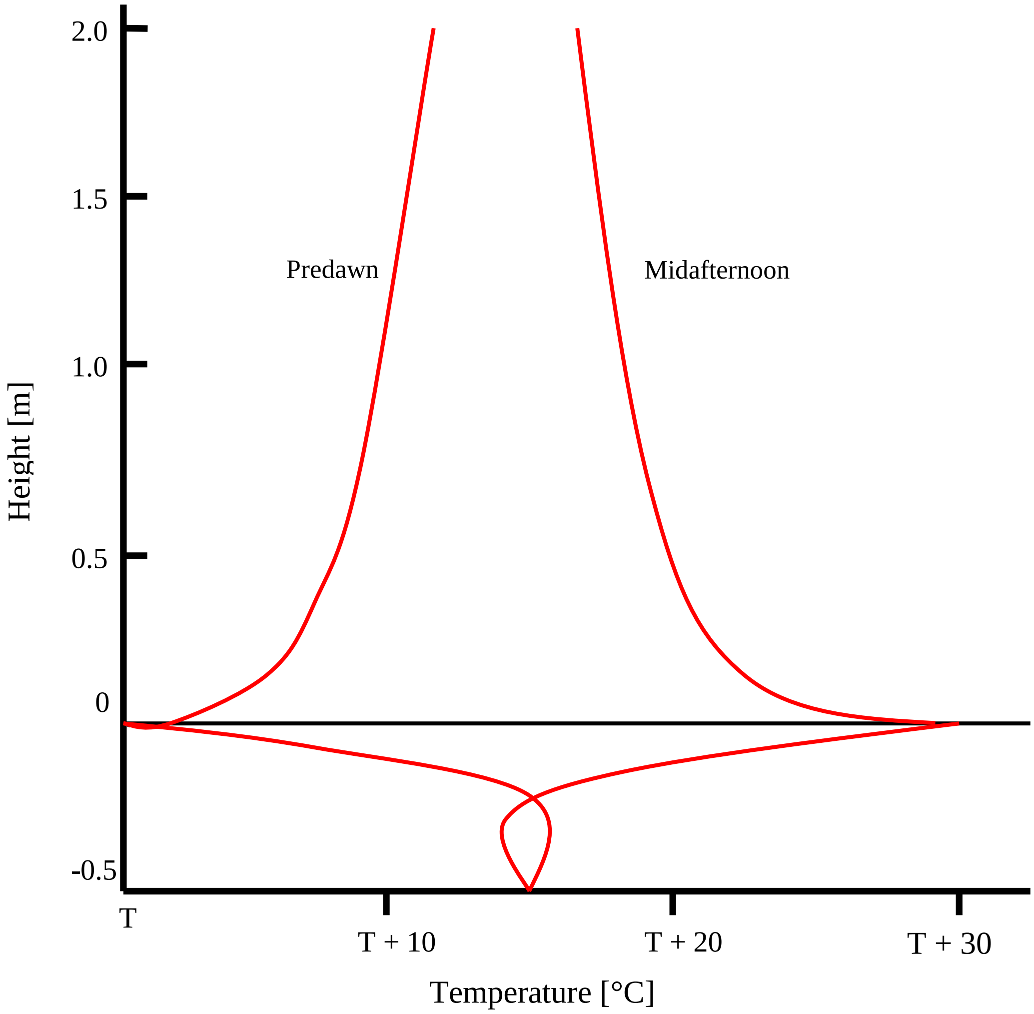


Figure 2.2 Temperature profiles (hypothetical) just above and below the soil surface on a clear, calm day [4, p. 10]

2.2.2 The effective temperature of the earth

The earth’s surface is constantly heated by absorbing solar radiation in the amount of:

$$(Q+q)(1-\alpha) \qquad (2.4)$$

Where:

Q = Direct beam radiation

q = Diffused radiation

α = Surface albedo

This in turn leads to the emission of long-wave, terrestrial radiation. This amount depends on the surface temperature and emissivity. If we assume that no long-period changes in the average temperature of the atmosphere are accruing, then equilibrium may be assumed between the streams of incoming solar radiation and outgoing terrestrial radiation [24, p. 84].

2.2.3 The energy balance of the earth-atmosphere system

In the atmosphere there is always a balance of energy. The balance may be influenced by the following:

- Greenhouse gases
- Surface radiation
- Latent heat [25, p. 80]

to name but a few.

If the solar radiation of 342W m^{-2} incident at the top of the atmosphere is expressed as 100 units, then, averaged over a long period of time, the sum of short-wave scattering and reflection to space and long-wave radiation from the surface and atmosphere must also total 100 units. Figure 2.3 illustrates these completed sets of energy flows [25, p. 80].

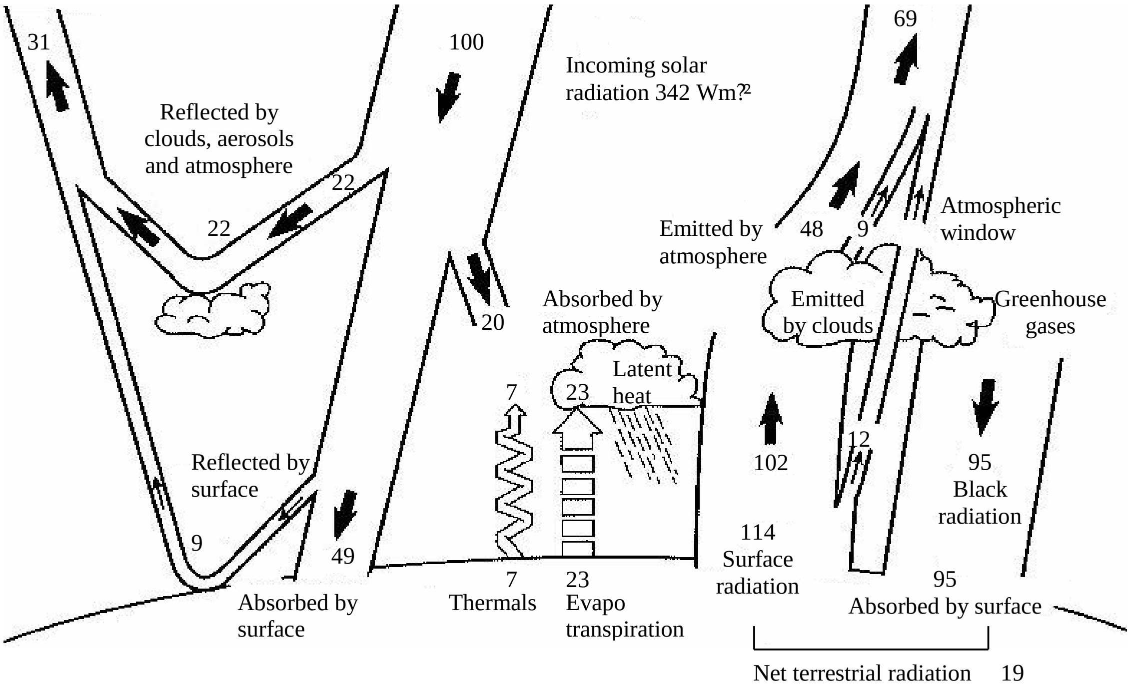


Figure 2.3 The annual mean global energy balance (modified after IPCC, 1996). The incoming solar radiation of 342W m^{-2} is taken to be 100 and all other quantities are scaled accordingly [25, p. 80]

The illustration can be summed up as follows:

- Of the 100 units 31 units are returned to space
- 20 units are absorbed by dust, water vapour and clouds
- 49 units heat up the earth’s surface

The net terrestrial radiation is 19 units, of which 7 units are absorbed by greenhouse gases and only 12 reach space through the window in the absorption spectrum.

Sensible and latent heat fluxes transfer 7 and 23 units of heat respectively into the atmosphere [25, p. 79].

2.2.4 Factors influencing air temperature

The following factors influence the air temperature in the planetary boundary layer (PBL).

- Type of air mass just above the PBL.
- Thermal characteristics of the surface and sub medium.
- Net radiation at the surface and its variation with altitude.
- Latent heat exchange during evaporation and condensation processes at the surface and in the air.
- Warm and cold air advection as a function of height in the PBL.
- Height of the PBL to which turbulent exchanges of heat are confined [1, p. 49].

2.3 Wind

Wind is the motion of air as a response to variation in atmospheric pressure [25, p. 83]. In a theoretical atmosphere in which no forces are operating, no air movement will occur. Once forces begin to operate and pressure surfaces are tilted, air will move horizontally and in accordance with Newton’s laws of motion [25, p. 83]. For horizontal variations in pressure, a force is created acting from across the pressure gradient from high to low pressure [21, p. 95].

Once the air starts to move under the influence of this pressure gradient force, it will be deflected to the left in the southern hemisphere due to the influence of the Coriolis force (an apparent force due to the rotation of the earth) and to the right in the Northern hemisphere. The result is that in the free atmosphere large-scale winds tend to blow parallel to the isobars (lines of constant pressure) with the wind speed dictated by the pressure gradient. Such flow is referred to as geostrophic. Near the surface an increase in friction causes retardation and a deflection across the isobars towards lower pressure. Usually it is found that the wind speed increases while the direction shifts anticlockwise with increasing height above the surface [21, p. 98].

2.3.1 Characteristics of atmospheric air movement

One of the obvious characteristics of wind is its variability. This is caused by a swirling or eddy motion of the air. It is also known as turbulent flow. These swirls or eddies are generated in two ways, mechanical and thermal. Mechanical turbulence occurs when wind moves over natural surfaces and the friction with the surface generates turbulence. Thermal or convective turbulence occurs when air is heated at the surface and moves upwards due to buoyancy. The fluctuations from mechanical turbulence tend to be smaller and more rapid than the thermal fluctuations [2, p. 33].

Convection is the term used to describe the differences in density ultimately brought about by differences in temperature. This involves the transfer of heat through the motion of hot fluid from one place to another. Convection can be natural or forced.

Convective cooling can be seen as the "wind chill" of non-living objects. Just as cold air molecules move and touch exposed skin, which is warmer than the wind blowing, carry away heat from the body, air molecules in motion carry away heat from a heated object, given that the air is colder that the heated object. The faster the air movement, the more heat is lost due to the heat transfer.

2.3.2 Wind profile relationship

Wind speeds increase with elevation above soil level due to less friction exerted on them from the surface. The surface tends to slow down the wind passing over it. The extent of this friction depends on the type of surface. Wind speed is at its slowest at the surface and increases with height. Figure 2.4 illustrates the relationship, conversion factor, of wind measures at certain heights above ground level to wind speed at 2m above ground level [12].

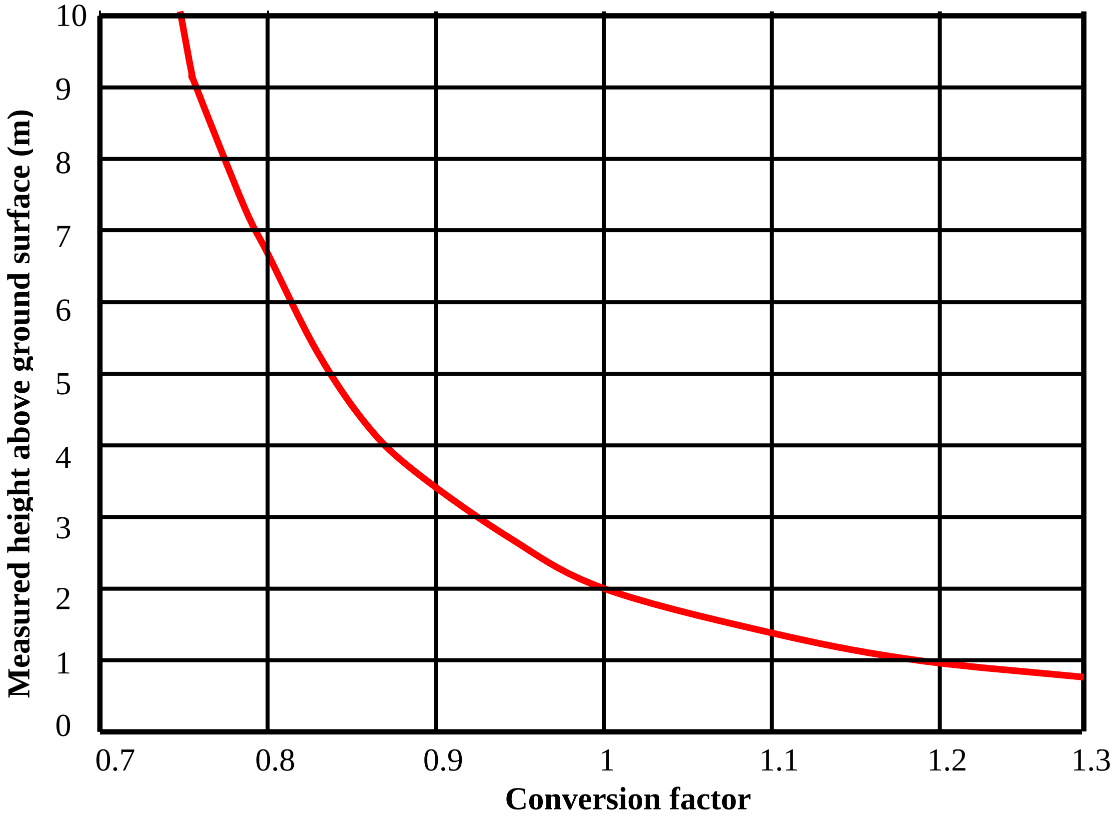


Figure 2.4 Conversion factor to convert wind speed measured at a certain height above ground level to wind speed at the standard height (2m) [12]

The following equation is useful for calculating conversion factors:

$$U_2 = U_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{2.5}$$

Where:

U_2 = Wind speed at 2m above ground in m s^{-1}

U_z = Measured wind speed measured at z m above ground in m s^{-1}

z = Height of the measurement above ground in metres [12]

2.3.3 Factors influencing wind

The following factors influence the wind in the planetary boundary layer (PBL).

- Large–scale horizontal pressure and temperature gradients in the lower atmosphere, which drive the PBL flow.
- The surface roughness characteristics, which determine the surface drag and momentum exchange in the lower part of the PBL.
- The earth’s rotation, which causes a deflection in the wind direction (the turning with height is due to reduced friction).
- The diurnal cycle of heating and cooling of the surface, which determines the thermal stratification of the PBL.
- The PBL depth, which determines wind shear in the PBL.
- Entrainment of the free atmospheric air into the PBL, which determines the momentum, heat, and moisture exchange at the top of the PBL, as well as the PBL height.
- Horizontal advections of momentum and heat, which affect both the wind and temperature profiles in the PBL.
- Large-scale horizontal convergence or divergence and the resulting mean vertical motion at the top of the PBL.
- Presence of clouds and precipitation in the PBL, which influence its thermal stratification.
- Surface topographical features, which give rise to local or mesoscale circulations [1, p. 67].

2.4 Water vapour in the atmosphere

Water may be present in the air as a solid, a liquid or as a gas. The process of evaporation occurs when a liquid changes to a gas. Sublimation is a change from a solid directly to a gas. Condensation, on the other hand, occurs is when a gas changes to a liquid and crystallization take place when a gas changes to a solid or when liquid changes to solid [25, p. 24].

With evaporation, sufficient kinetic energy is gained through collisions with adjacent molecules in order to overcome the attractive force between the liquid molecules. As the molecule escapes, it takes kinetic energy with it which leaves the water surface with less total kinetic energy. The loss in kinetic energy cools the surface. Thus evaporation is dependent on the water temperature. Energy involved in phase changes is equal to latent heat [15].

With condensation, molecules are moving slowly enough and are pulled back to the water surface by the attracting forces. The molecule plunges into the water, transferring energy to the molecules near where it hits the surface of the liquid. The addition of energy heats the surface. Condensation is thus dependent on the air temperature [15].

2.4.1 Relative humidity

Relative humidity is a term used to describe the quantity of water vapour present in a gaseous mixture of air and water. It is defined as the ratio of the partial pressure of water vapour in a gaseous mixture of air and water to the saturated vapour pressure of water at a given temperature [21, p. 63]. Relative humidity is thus a ratio of how saturated the air is at a given temperature. Humidity should always be thought of in terms of energy. There is a connection between humidity and air temperature, but the connection has nothing to do with water being “held” by the air. The air is only the delivery system [15]. Relative humidity will change if the amount of moisture in the air changes or if the amount of moisture in the air remains the same but the temperature changes. Relative humidity is normally expressed as a percentage and is defined in the following manner:

$$RH = \frac{\rho(H_2O)}{\rho*(H_2O)} \times 100\% \qquad (2.6)$$

Where:

RH = Relative humidity of the mixture being considered

$\rho(H_2O)$ = Partial pressure of the water vapour in the mixture

$\rho*(H_2O)$ = Saturated vapour pressure of the water at the temperature of the mixture [20]

In weather forecasting and reporting, relative humidity is an important metric as not only is it an indicator of the likelihood of rain, dew or fog, but it also increases the apparent temperature to humans by hindering the evaporation of perspiration from the skin as the relative humidity rises [20].

Relative humidity expresses how much of the available energy has been used to “free” liquid water molecules. A relative humidity of 50% means half the available energy has been used to evaporate water from, e.g., ground, streams and dams, and 50% is still available for more evaporation [15].

As air temperature is a function of relative humidity, relative humidity will drop by a factor of 2 for every 11.1°C increase of air temperature, assuming conservation of absolute moisture.

2.4.2 Factors influencing humidity

The following factors influence the humidity in the planetary boundary layer (PBL):

- Specific humidity of air mass just above the PBL.
- Type of surface, its temperature, and availability of moisture for evaporation and/or transpiration.
- The rate of evapotranspiration or condensation at the surface and the variation of water vapour flux with height in the PBL.
- Horizontal advection of water vapour as a function of height.
- Mean vertical motion in the PBL and possible cloud formation and precipitation process.
- The PBL depth through which water vapour is mixed [1, p. 49].

Chapter 3

Thermography

3.1 Introduction

Infrared thermography is the study of temperature variations through infrared-sensitive equipment. The application of infrared thermography spreads into many fields including electrical, mechanical, construction, insulation, aeronautics and medical, to name but a few. Thermography aids in locating and predicating potential problems pertaining to heat loss or heat distribution. Temperature is a key condition indicator associated with deterioration of equipment. For example, a number of conditions in an electrical system can affect the life of the system, namely localized overheating. The magnitude of this problem may be calculated by Joule's law in that a small change in resistance will result in a doubling of current [6, p. 216].

Figure 3.1 illustrates this law where there is a concentration of heat near the clamp connection due to an improper connection between the clamp and the cable.

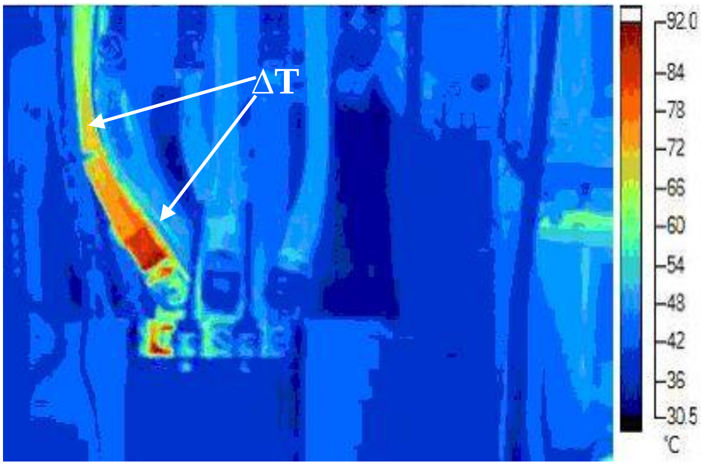


Figure 3.1 Infrared image showing a hotspot

The severity of the illustrated hotspot is directly proportional to the load. The direction of the ΔT points towards the source of the problem as can be seen in figure 3.1.

Depending on the use, thermography may be qualitative or quantitative. Qualitative refers to heat patterns which are analysed, and quantitative refers to radiometric temperature measurements, where the differences in near exact temperatures are used to determine the severity of the problem by means of statistical analysis.

Nearly all objects emit, reflect or transmit electromagnetic radiation of a wavelength depending on the object's temperature. The electromagnetic spectrum is the complete range of all possible electromagnetic radiation as seen is figure 3.2 [8, p. 2-1].

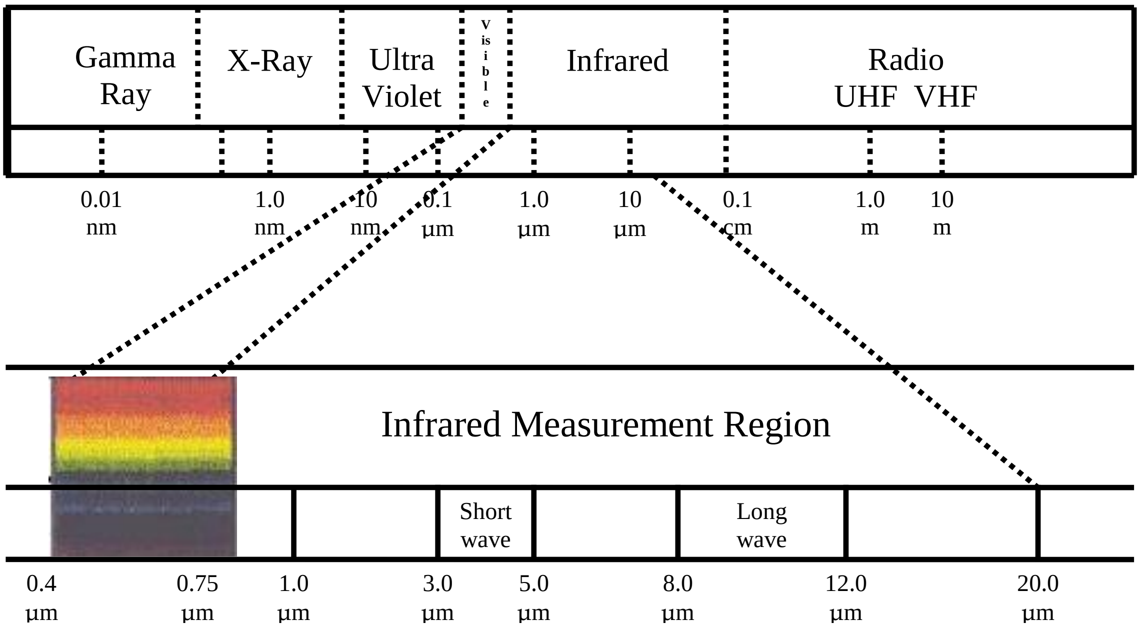


Figure 3.2 Electromagnetic spectrum [8, p. 2-1]

The electromagnetic spectrum begins with the longest radio waves, extending through visible light all the way to the extremely short gamma rays, which are a product of radioactive atoms. The entire range of radiation extends in frequency from approximately

10^{23} Hz to 0 Hz or, in corresponding wavelengths, from 10^{-13} centimetres to infinity and includes, in order of decreasing frequency, cosmic-ray photons, gamma rays, x-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves [2].

Electromagnetic energy at a particular wavelength λ (in vacuum) has associated frequency f and photon energy E. Thus, the electromagnetic spectrum may be expressed equally well in terms of these three quantities. They are related according to the equation:

$$c = f \times \lambda \tag{3.2}$$

and

$$E = hf \tag{3.3}$$

or

$$E = \frac{hc}{\lambda} \tag{3.4}$$

where:

c = Speed of light

f = Frequency

λ = Wavelength

E = Energy

h = Planck's constant, $\left(h \approx 6.626069 \cdot 10^{-34} J \cdot s \approx 4.13567 \mu eV / GHz\right)$

High frequency electromagnetic waves have a short wavelength and high energy; low-frequency waves have a long wavelength and low energy [9].

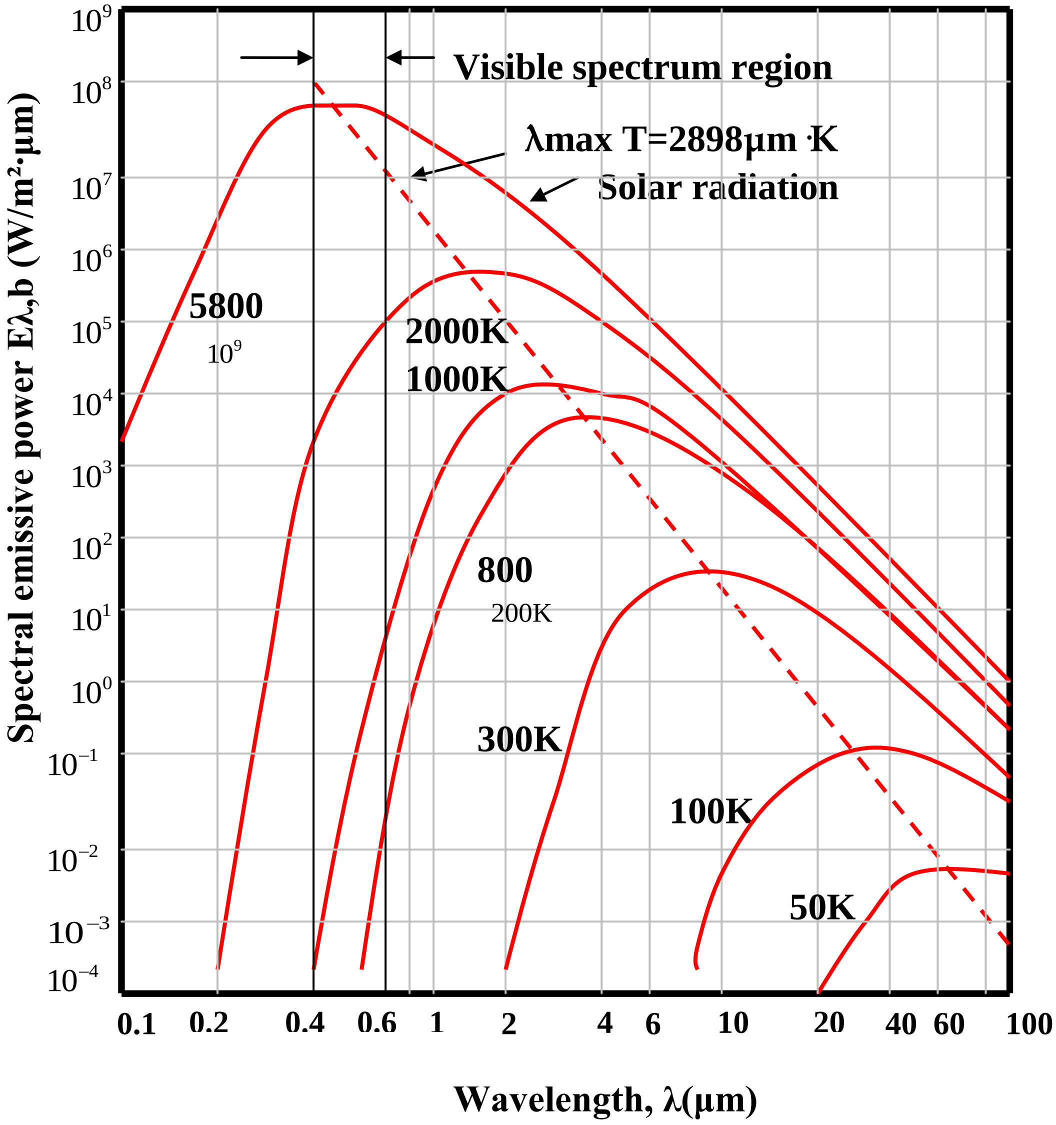


Figure 3.3 Planck's curve [7, pp. 647-648]

Max Planck derived a curve which is shown in figure 3.3 where this phenomenon can be seen clearly. When examining the curve, the following is evident:

- There is a continuous variation in emitted radiation with wavelength.
- At any wavelength the magnitude of the emitted radiation increases with increasing temperature.
- Temperature determines the spectral region in which the radiation is concentrated, with comparatively more radiation appearing at shorter wavelengths as the temperature increases.

- A significant fraction of the radiation emitted by the sun is in the visible light region of the spectrum [7, pp. 647-648].

The relationship between maximum wavelength and temperature is expressed in Wien's displacement law.

$$\lambda \max T = C_3 \qquad (3.5)$$

Where:

λ = Wavelength

T = Temperature

C_3 = Third radiation constant (C_3 = 2897.8 µm · K)

This is law is plotted as a dashed line in figure 3.3 [7, pp. 647-648].

3.2 What is infrared?

Infrared energy is light that we cannot see with the naked eye, but our bodies can detect it as heat and it forms part of the electromagnetic spectrum. Infrared energy is comprised of those frequencies that exist just below the red end of the visible spectrum. Figure 3.2 shows the thermal range in more detail.

3.2.1. Infrared sub-divisions

Infrared may be subdivided into 5 sub-divisions:

3.2.1.1. Near-Infrared: 0.75-1.4µm in wave length. This wavelength is commonly used in fibre optic telecommunication because of low attenuation losses. Image intensifiers are also sensitive to this area of the spectrum. Examples include night vision devices such as night vision goggles [3, pp. 21-22].

3.2.1.2. Short-wave: 1.4-3µm in wavelength. This is used in long-distance telecommunication as well as in medical thermography to detect cancer at an early stage [3, pp. 21-22].

3.2.1.3. Mid-wave: 3-8µm in wavelength. Uses includes guided missile technology or what is commonly known as “heat seeking” missiles [3, pp. 21-22].

3.2.1.4. Long-wave: 8-15µm in wavelength. This is also known as the thermal imaging region in which sensors can obtain a passive picture based on thermal emissions only and requiring no external light or thermal source [9].

3.2.1.5. Far-Infrared: 15-1,000µm in wavelength. Far-infrared lasers operate in this waveband [3, pp. 21-22].

3.3 Heat energy

Heat can be described as the transfer of energy. When heat flows, it is energy that is being transferred between objects. Thus, heat is energy that is transferred from one body to another because of a difference in temperature. Heat energy is calculated in joules [7, p. 486].

The sum total of all the energy of all the molecules in an object is called its thermal energy or internal energy. Heat flow direction between two objects is independent of their thermal energy, but dependent on the temperature of those objects.

The degree of temperature increase when heat is applied to an object is referred to as specific heat and is expressed in the equation

$$Q = mc\Delta T \tag{3.6}$$

Where:

Q = Change in temperature

m = Mass of the object

c = Specific heat quantity of the material

T = Temperature

The first law of thermodynamics states that, in a closed system, the energy entering the system equals the energy leaving the system. This law can also be expressed as an equation

$$\Delta U = Q - W \tag{3.7}$$

Where:

Q = Net heat added

W = Net work done by the system

The first law of thermodynamics is also known as the law of conservation of energy.

Energy conservation does not always happen in nature and due to this the second law of thermodynamics was formulated. This law states that heat flows from a hot object to a cold object; heat will not flow spontaneously from a cold object to a hot object [7, p. 516].

Kirchhoff quantified how photons react when they interact with a surface.

$$R + A + T = 1 \tag{1.2}$$

Where:

R = Reflection

A = Absorption or emitted

T = Transmitted.

In condition monitoring most objects are transparent to infrared, thus $R + E = 1$.

X-rays are a good example of transmitted energy. When radiation is transmitted through a material it does not affect that material.

Reflection can best be seen in light being reflected by a mirror. Secular reflection occurs on smooth surfaces such as mirrors, while diffused reflection occurs on rough surfaces such as a painted wall. When radiation is reflected by a material it does not affect that material. Reflection is challenging for thermographers as it can result in false indications or masking of problems.

A material can absorb radiation just like the human skin absorbs ultraviolet radiation from the sun. When radiation is absorbed by a material, some of the radiated energy is transferred to the material and is then re-radiated or re-emitted as radiation of a longer wavelength [11].

The ability of a material to retain its absorbed energy is known as the heat capacitance of the material. In a homogeneous material with known physical properties, the heat capacitance is the mass of the material multiplied by the specific heat capacitance. Think of a swimming pool in summer. Water has a high heat capacitance and thus does not easily lose its energy to the surroundings [23]. Larger pools will have more mass and thus a higher heat capacitance. Heat capacitance is “inertia” against temperature fluctuations, also referred to as the thermal flywheel effect. Ideal materials for heat capacitance have a high specific heat capacitance and high density. Thus, any solid, liquid or gas that has mass will have some heat capacitance.

3.4 Black body

A black body is a theoretical object that absorbs 100% of the radiation that hits it. Therefore, it reflects no radiation and appears perfectly black. In practice no material has been found to have 100% absorption. Carbon in its graphite form only reflects about 3% of the incoming radiation. At a particular temperature the black body would emit the maximum amount of energy possible for that temperature. This value is known as the black body radiation or emissivity [11]. It is expressed as a factor between 0 and 1 where 1 represents a black body and 0 a very shiny material. The emissivity of a surface is the ratio of the energy from it to that from a black body at the same temperature, the same wavelength and under the same viewing conditions [11].

3.5 Energy transfer

Heat energy is the transfer of heat from one place, or body, to another by movement of fluids. When there is a temperature difference between an object and the surroundings, a transfer of thermal energy occurs. This transfer will be from the warmer object to the cooler object. Heat transfer can never be stopped between objects at different temperatures, it can only be decreased [5]. The transfer of heat will continue as long as there is a difference in temperature between two locations. Once the two locations have reached the same temperatures, thermal equilibrium is established and the heat transfer stops. The rate at which temperature changes, is proportional to the rate at which heat is transferred. The way of transfer as well as the rate at which it occurs is important to the thermographer to enable him/her to correctly categorize the severity of a hotspot according to the surrounding conditions [5].

Heat energy may be transferred in one of three ways or as a combination of two or all three [3, p. 503].

3.5.1 Conduction

Conduction is the transfer of heat by means of molecular collisions. As one end of an object, such as a metal poker in a hot fire, is heated, the molecules at the heated end move faster. As they collide with their slower moving neighbours, they transfer some of their energy to those molecules whose speed then increases. These in turn transfer some of their energy by collisions with molecules still further along the object. Heat conduction only takes place if there is a temperature difference. Thermal conductivity describes the heat flow through a uniform object [3, p. 503].

A good industrial example of this is a poor conductor clamp joint. An increase in resistance results in heat being generated “inside” the clamp. This internal heat is conducted to the outer surface of the clamp which can be detected with a thermal imager. It is also important to remember that the measured surface temperature is not the same as the generated temperature. The rate of the heat flow as well as the surface conditions, will determine the measured surface temperature.

According to Fourier, the rate at which heat energy is transferred by conduction can be expressed by the following equation [23]:

$$Q = \frac{k}{L} \times A\Delta T \qquad (3.8)$$

Where:

Q = Heat energy

k = Thermal conductivity value

L = Thickness of the material

A = Area

ΔT = Temperature difference.

The conductivity value is defined as the quantity of heat energy that is transferred through a one square metre piece of material that is one centimetre thick during one hour when there is a 1°C temperature difference across the material. Materials with a high k value are good conductors [23]. Good conductors of heat energy are normally good conductors of electricity as well, for example, copper, aluminum and steel.

3.5.2 Convection

Convection is the process whereby heat is transferred by the mass movement of molecules from one place to another. Whereas conduction involves molecules and/or electrons moving only over small distances and colliding, convection involves the movement of molecules over large distances.

Convection can be forced or natural. Forced convection occurs, for example, when a fan blows heated air from a furnace into a room. Natural convection occurs when hot air rises due to buoyancy forces. For instance, the air above a radiator expands as it is heated, and hence its density increases; because its density is less, it rises, just as a log submerged in water floats upwards because its density is less than that of the water. Wind is another example of convection, and weather, in general is a result of convective air currents [3, p. 505].

Figure 3.4 illustrates a pot of water that is heated. During the heating process convection currents are set up as the heated water at the bottom of the pot rises due to its reduced density and is replaced by cooler water from above. Many heating systems make use of this principle where the water temperature is heated to cause expansion and rising. This then causes the water to circulate in the system [5, p. 505].

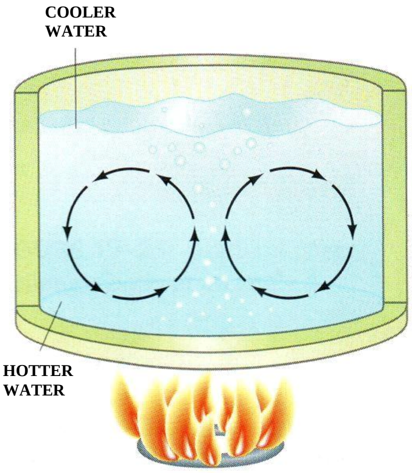


Figure 3.4 Convection currents in a pot of water being heated on a stove [3, p. 505]

The rate at which convection occurs depends on several factors which are expressed in Newton’s law of cooling:

$$Q = h \times A\Delta T \tag{3.9}$$

Where:

Q = Heat energy in Watt or Btu/h

h = Convective heat transfer coefficient

A = Area

ΔT = Temperature difference.

The convective heat transfer, also known as a film coefficient, defines the heat transfer due to convection and represents the thermal resistance of a relatively stagnant layer of fluid between a heat transfer surface and the fluid medium. The value of h also depends on the:

- relative velocity of the fluid (fluid-surface);
- temperature difference between the surface and the fluid;
- direction of the heat flow;
- surface size and orientation;
- fluid material properties;
- surface roughness [10].

3.5.3 Radiation

Radiation is energy transfer from the sun to the earth. Convection and conduction require the presence of a medium to carry the heat from the hotter to the colder region. Radiation, on the other hand, occurs without any medium.

The rate at which an object radiates energy is proportional to the fourth power of the Kelvin temperature scale, T. A body at 2000K will radiate energy at a rate of $2^4 = 16$ times greater than one at 1000K. The rate of radiation is also proportional to the area A of the emitting object. So the rate at which the energy leaves the body is summarized in the Stefan-Boltzmann equation [23].

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A T^4 \qquad (3.10)$$

Where:

ε = Emissivity

σ = 5.67 x 10^{-8} W/m^2K^4

A = Area

T = Temperature in Kelvin or Rankin

The emissivity factor, ε, is a number between 0 and 1 that is characteristic of the material. Very black surfaces, such as charcoal, have an emissivity close to 1, whereas bright shiny surfaces have an emissivity close to zero and thus emit correspondingly less radiation. Not only do shiny surfaces emit less radiation, they also absorb little of the radiation that falls upon them, as most is reflected. Bodies with an emissivity close to 1 absorb nearly all the radiation that falls on them. Thus, a good absorber is a good emitter.

A body not only emits energy by radiation, but also absorbs energy radiated by other bodies. The net rate of radiant heat flow from an object is given by the equation:

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A \left(T_1^4 - T_2^4\right) \qquad (3.11)$$

Where:

σ = 5.67 x 10^{-8} W/m^2K^4

ε = Emissivity at T_1

A = Surface area of the object

T_1 = Object temperature

T_2 = Surrounding temperature

When $T_1 = T_2$, equilibrium is reached between the object and its surroundings. For that $\frac{\Delta Q}{\Delta t}$ must be equal to zero. This confirms the fact that a good emitter is a good absorber.

Equation 3.11 cannot be used to calculate the heating of an object by radiation from the sun since this equation assumes a uniform temperature T_2, of the environment surrounding the object, whereas the sun is essentially a point source [3, p. 506].

3.6 Thermal imagers

Thermal imagers are used to identify thermal patterns that cannot be seen in the visual spectrum but only in the infrared spectrum. Thermal imagers are electronic imaging cameras that detect infrared radiation as a camcorder detects visible light. Both detect forms of electromagnetic energy that are radiated by all objects above absolute zero [17]. Not all heat patterns detected with a thermal imager point towards a problem. Some equipment should be hot to indicate that it is in good working condition. An example of this is a heat sink on an electronic circuit board.

Thermal imagers differ in size, technology and ability between manufacturers. There is a constant competition between manufacturers to produce the “best” thermal imager. Some manufacturers have even designed specific imagers to perform specific inspections. This may vary from building and electrical inspections to safety and automotive driver vision enhancement. Since the 1950’s, when liquid nitrogen was used to cool down bulky equipment, the thermal imager design and image quality have improved greatly, and equipment has become more affordable [17].

3.6.1 Components of a thermal imager

Thermal imagers seem like complex electronic devices. Common components of a thermal imager can be seen in figure 3.5 [16, pp. 2-16].

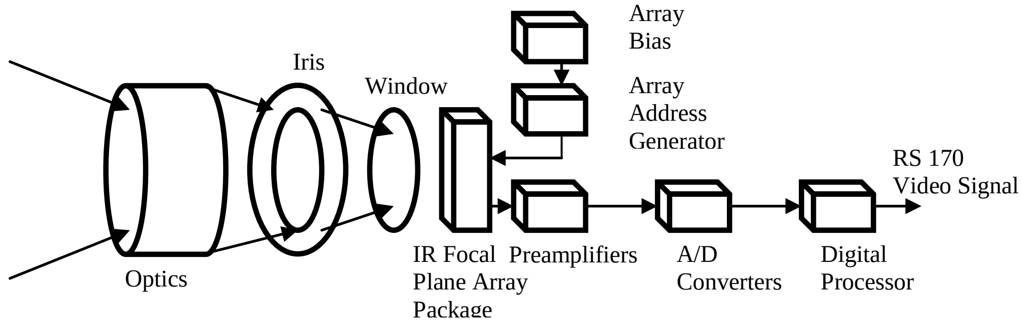


Figure 3.5 Configuration of a typical IRFPA imager (courtesy of Honeywell corp.) [16, pp. 2-16]

3.6.1.1 Lens

The lens allows incoming infrared radiation to focus on a detector. Thermal imager lenses are designed to operate over a set waveband. One may ask how infrared radiation can pass through glass which is opaque. To overcome the problem thermal imaging lenses are commonly coated with germanium (Ge), silicon (Si) and zinc selenide (ZnSe). These filters, as they are often called, allow the infrared radiation to pass through the glass lens onto the detector although it is opaque to the human eye. The type of coating also determines the operating bandwidth of the imager and for what application it will be used.

Figure 3.6 and figure 3.7 show the sensitivity of germanium and zinc selenide filtering wavelengths between 8-12µm [13].

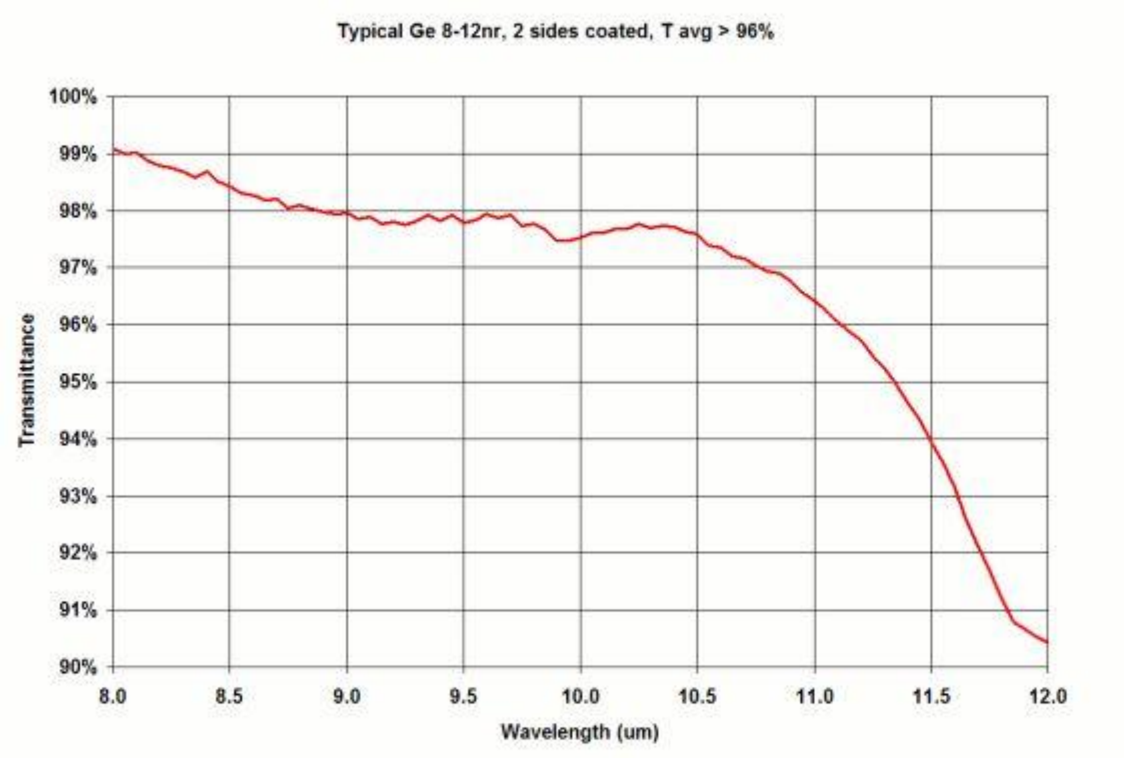


Figure 3.6 Sensitivity of germanium lens coatings

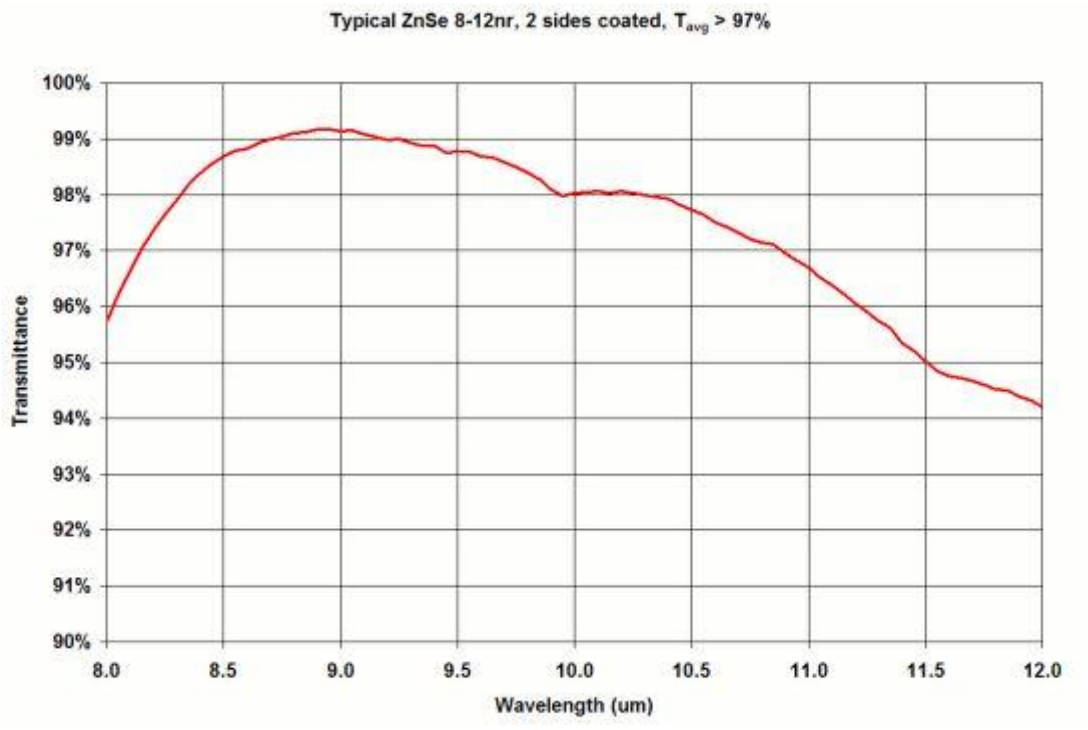


Figure 3.7 Sensitivity of zinc selenide lens coatings

Lens care of thermal imagers is extremely important as scratching of the lens will result in more visible light passing through the infrared “filter”, leading to inaccurate results [13]. Dirt or dust on the lens should be removed with caution and care.

Lens selection is a very important factor when buying a thermal imager. The two main factors to consider are the field of view and the minimum focus. Wide angle lenses are used in small confined areas where a long minimum focus is needed. Telephoto lenses are used outdoors to reduce the effect that components being inspected appear small and far away. Not all thermal imagers will have the luxury of the user being able to change the lens. In such cases the imager needs to be sent back to the manufacturer. Where the user is able to change the lens, the new lens needs to be entered into the imager’s software.

3.6.1.2 Detector

The radiation that passes through the lens is focused on the detector where it produces a measurable response, either as an electrical charge or a change in resistance. Materials commonly used for detectors are platinum silicide (PtSi), mercury cadmium telluride (HgCdTe) and indium antimonide (InSb).

The detector size describes the amount of displayed points per image of a thermal imager. A detector of 160 x 120 captures and displays more than 19 000 measuring points with each measurement. Detector sizes may go as high as 640 x 480. Bigger detectors allow for more measuring points and better the spatial resolution. However, this does not guarantee more accurate temperature readings of small objects. The thermal sensitivity of the detector will be the determining factor. An example of this is the Fluke Ti55FT with a detector of 320 x 240 with a pitch of 2.5 micron will have a thermal sensitivity of

≤0.05°C at 30°C compared to a Fluke Ti10 with a detector of 160 x120 and a thermal sensitivity of ≤0.2°C at 30°C.

3.6.1.3 Processing electronics

The processing electronics take the response from the detector, process it electronically into a thermal image, a temperature measurement or both.

3.6.1.4 Controls

The input of infrared radiation or the output of data may be controlled by various control systems. These include the following:

3.6.1.4.1 Temperature range, span and thermal level

The temperature range represents the “thermal window” through which the operator is able to look and measure data. Certain systems have a preset range and other systems automatically set the range. Within a range it is possible to set a temperature span. For a wider span less thermal detail will be detected and vice versa. Beware of a too narrow span, as this causes “noise”. With this in mind select a span that will represent all the temperatures concerned. The hottest object will be at the top of the range and the coldest at the bottom. Temperatures outside the selected range, above or below, will be saturated and the user will not be able to measure the object’s temperature. The correct level and span will result in better thermal detail. Figure 3.8 represents a poor range selection of a human face, between 27°C and 37°C. In this image much of the face is saturated due to the incorrect selected level and span.

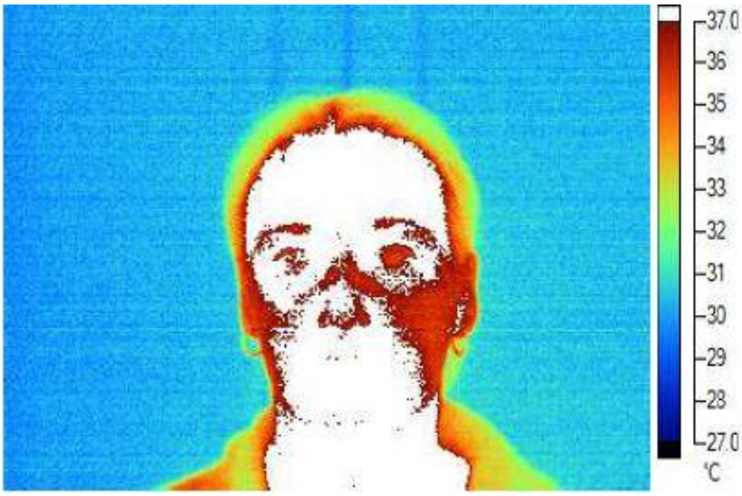


Figure 3.8 Incorrect level and span when taking an image of the human face

Figure 3.9 represents a better range selection of a human face, between 30°C and 40°C, with no saturation.

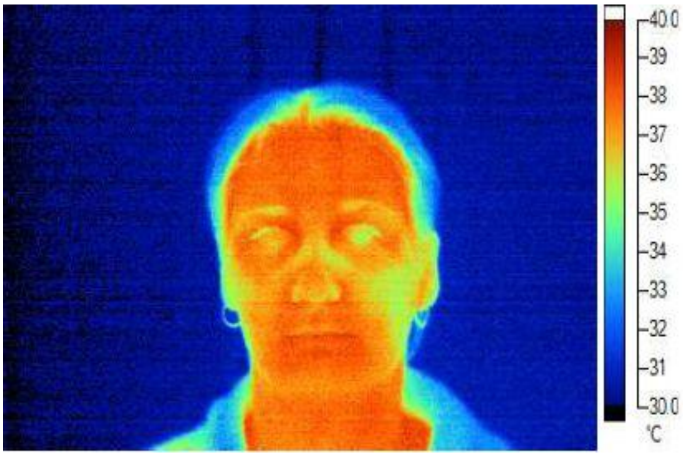


Figure 3.9 Typical level and span when taking an image of the human face

The level represents the centre value of the range and span. Figure 3.9 shows a typical level and span of the human face, between 30°C and 40°C.

3.6.1.4.2 Focus

Focus is an important factor when taking a thermal image. An out of focus image will result in inaccurate temperature measurements when collecting qualitative measurements.

3.6.1.4.3 Colour palette

The colour palette is a colour representation of the temperatures being displayed in an image. Certain colour palettes get preference over others depending on the application and/or problem. There are 8 common colour palettes used. They are:

- Grayscale, figure 3.10
- Grayscale inverted, figure 3.11
- Blue – red, figure 3.12
- High-contrast, figure 3.13
- Hot metal, figure 3.14
- Iron blow, figure 3.15
- Amber, figure 3.16
- Amber inverted, figure 3.17

Figure 3.10 Grayscale palette

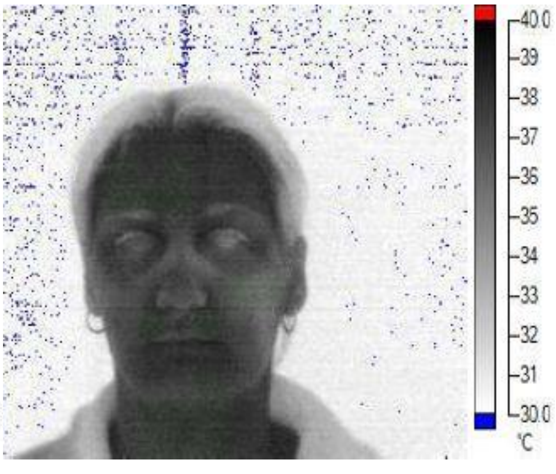


Figure 3.11 Grayscale inverted palette

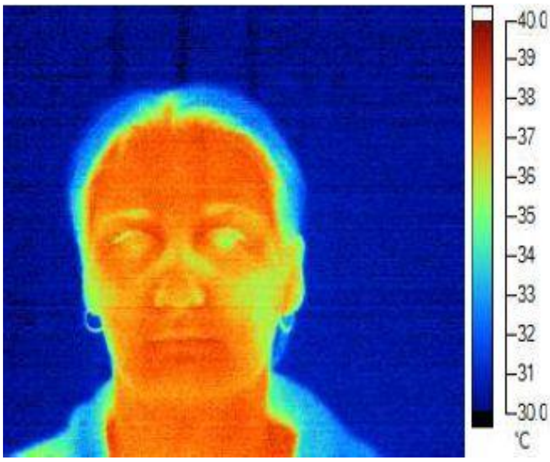


Figure 3.12 Blue – red palette

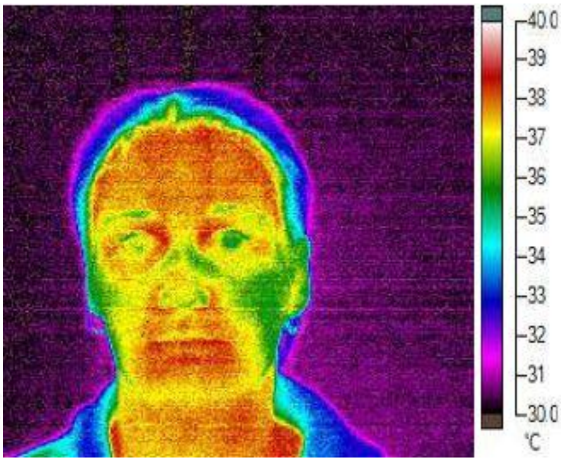


Figure 3.13 High-contrast palette

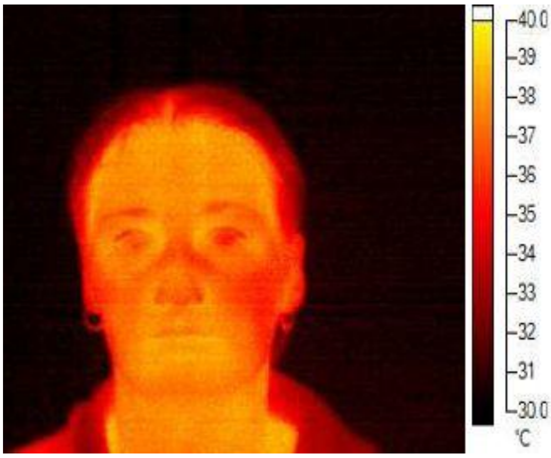


Figure 3.14 Hot metal palette

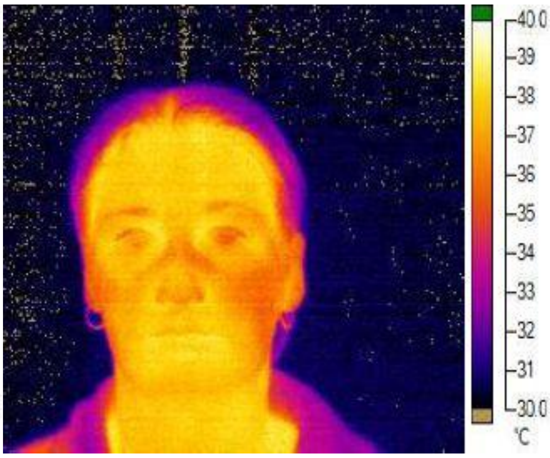


Figure 3.15 Iron blow palette

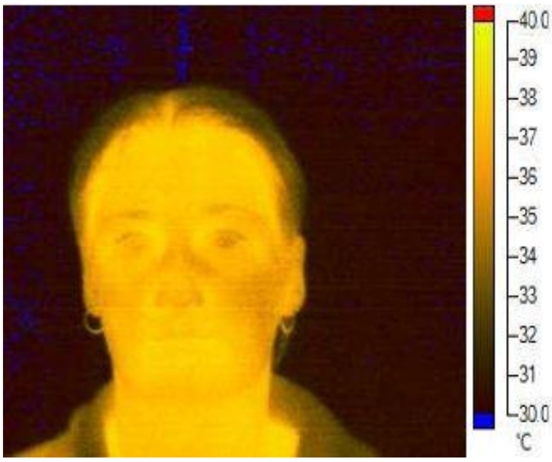


Figure 3.16 Amber palette

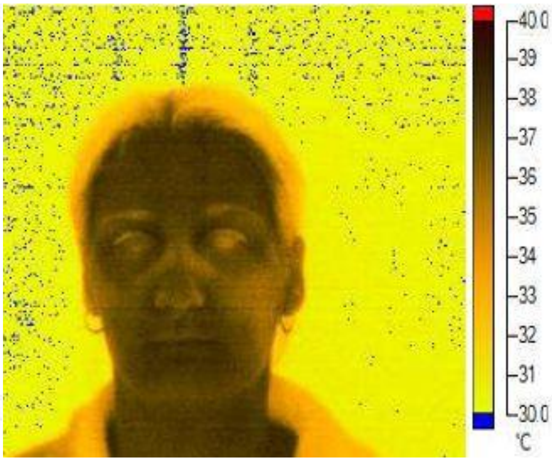


Figure 3.17 Amber inverted palette

3.6.1.5 Display

The display differs from one manufacture to another. The most common ones are the view finder and the LCD display. Some manufacturers use both these forms of display on a single unit while others make use of only one at a time. The size of the display differs between the models. Video or S-video outputs are another form of display which enables the user to show the image on any external monitor or record it on a video recorder.

3.6.1.6 Power

Batteries are used to power the mobile thermal imager. Most systems use NiCad, metal hydride batteries or lead acid batteries. Depending on the manufacture and model, an AC power supply may be connected as an additional power source.

3.6.1.7 Data storage

Data can be stored either as a still image or as an analog video image. Digital data can be stored in 8-bit or 12-bit. 8-bit data cannot be modified after the image has been captured whereas 12-bit can. This makes it possible to highlight certain areas of an image for reporting purposes.

3.6.2 Performance factors of thermal imagers

When using/buying a thermal imager there are a few factors that need special attention. It is important to understand the capabilities of the thermal imager and to work within its physical and optical limitations in order to detect potential problems more accurately. The imager to be used must be suitable for the type of application it is intended to be used for.

3.6.2.1 Field of view (FOV)

Field of view (FOV) can be described as the total area that is seen by the camera when using a specific lens, much like the view through a windshield of a car while driving. This is like a rectangle extended outwards from the centre of the imager lens. The farther away you look, the larger the rectangle becomes. This is illustrated in figure 3.18.

Field of view is measured in a circular or rectangular angle of view. FOV might be expressed as 18° or 20° (horizontal) x 15° (vertical) for a 50mm lens [22].

3.6.2.2 Instantaneous field of view (IFOV)

Instantaneous field of view (IFOV) is the spatial resolution characteristics of an infrared imager, or the smallest object that can be seen by the system at a given distance. IFOV is generally specified in millenarians (mRad). If FOV is the view through a windshield of a car, then IFOV is the smallest object that can be seen though that same windshield [22]. This means that, at a certain distance, you would not be able to detect a small hotspot if the spatial resolution of the imager is not good.

3.6.2.3 Measurement instantaneous field of view (IFOVmeas)

Measurement instantaneous field of view (IFOVmeas) describes the radiometric measurement resolution of the system. This is also expressed in mRad. IFOVmeas defines the smallest object that can be measured radiometrically at a given instant at a certain distance [22].

$$\text{Distance to target x IFOVmeas} = \text{Measurement spot size} \qquad (3.12)$$

Figure 3.18 summarizes the performance factors FOV, IFOV and IFOVmeas.

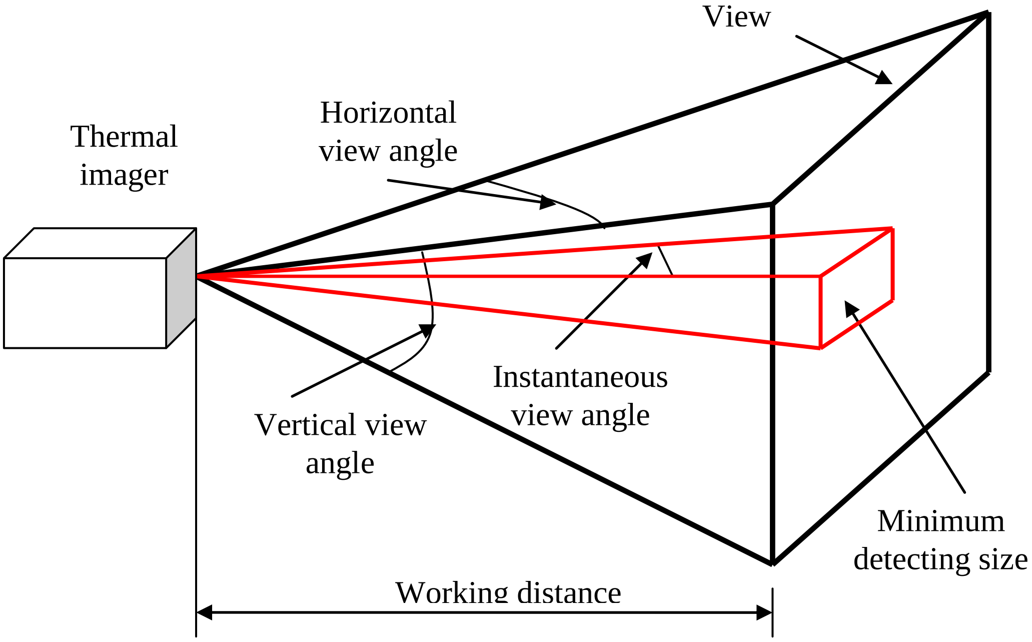


Figure 3.18 Relationships between FOV, IFOV and IFOVmeas

3.6.2.4 Minimum resolved temperature difference (MRDT)

Minimum resolved temperature difference (MRDT) measures the performance of a thermal imager’s thermal sensitivity. This is also called the noise equivalent temperature difference (NETD). This value is typically 0.2°C at 30°C [22].

3.6.2.5 Spatial Sensitivity

Spatial sensitivity is the ability of a system to see detail.

3.6.3 Factors to consider with thermal imaging

When doing a thermal inspection the following factors may have a direct or indirect influence on the results. By knowing the degree of influence of these factors the thermographer will be able to draw more accurate conclusions with regard to heat transfer and the severity of the problem.

- Ambient temperature – Heat is transferred from a hot object to the colder surrounding air resulting in lower measured temperatures which can influence the severity of the problem
- Background temperature – Reflections of the background may appear in the image and affect the temperature measurements.
- Relative humidity – Heat will be transferred more rapidly from the object to the surrounding air if the relative humidity is high. This is because high relative humidity is more common in low ambient air temperatures.
- Distance to object – The maximum distance is determined by the spot size and the IFOVmeas of the imager.
- Wind – Convection cools down hot surfaces as the moving air "grabs" the heat molecules and transfers them away from the hot object.
- Solar radiation
- Load information - The influence of a small change in resistance will result in a doubling of current. The severity of a hotspot will increase with an increase in load.
- Emissivity – A low emissivity object's reflection is higher than that of objects with a close to 1 emissivity.

Chapter 4

Thermal imager tests

4.1. Introduction

A Fluke Ti55FT thermal imager was used to perform the experiments in which the degree of influence of the three climatic elements, i.e. ambient temperature, relative humidity and wind, was tested against before and after images. The Fluke Ti55FT thermal imager spectral band is between 9µm and 14µm and its thermal sensitivity (NETD) is ≤0.05°C at 30°C. The detector is a 320 x 240 focal plane array with a 54mm telephoto lens. For more technical specification refer to annexure A, the manufacturer's data sheet for the FLUKE Ti55FT thermal imager.

Prior to the experiments, a few simple tests were performed to test the thermal imager's performance against that of the manufacturer's data sheet, annexure A. This is to assure that it is still within the permitted specifications to obtain reliable results. These tests comprise of the following:

- Image non-uniformity
- Long-term offset drift
- Offset variations over observed ranges
- Spatial resolution
- Thermal flooding
- Thermal resolution

4.2 Thermal imager tests

4.2.1. Image non-uniformity

This test is designed to determine the non-uniformity of the focal plane array which is caused by inevitable drift of individual pixels. This effect will influence the accuracy of the intra-image temperature difference measured and is caused by a poor lens.

To test, take a container of water at room temperature. Switch the camera on and allow it to settle (about 1 to 2 hours). Set the camera to an emissivity of 0.99 at a distance of 1m from the container of water and to a very narrow temperature range, around the temperature of the water. For example, if the water is 25°C, set the range to between 23°C and 27°C. Measure the water temperature with a thermometer if thermocouples are not available [14].

After the camera has settled, stir the water for 30 seconds to produce a homogeneous temperature distribution at the surface. Point the camera perpendicularly towards the water surface from a distance of 1 metre and record an image [14].

4.2.1.1 Results of the image non-uniformity test

During this experiment a small temperature difference, 0.1°C, was detected between the centre of the water bath and the left edge of the water bath, while the right side of the water bath was at the same temperature as the centre. This can be seen in figure 4.1. The fact that the temperature difference only occurs on one side might be attributed to reflections, but it is marginally small and can be ignored.

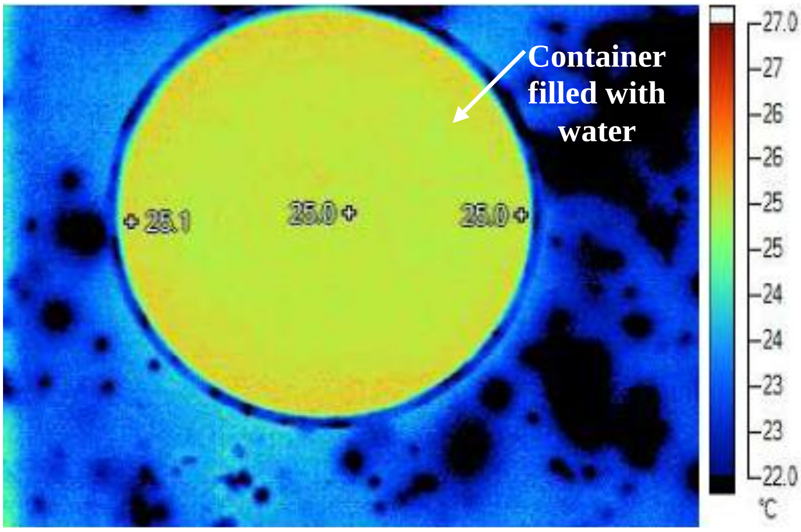


Figure 4.1 Image non-uniformity results

4.2.2. Long-term offset drift

With age, electronic components inside a thermal imager will lead to slow changes in signal amplification, internal temperature references and other control circuitry. Long-term drift can have an effect on long durational studies. The severity will differ with the duration of the study.

For this test one needs a container with ice and water. Adjust the room temperature on the imager to the exact room temperature. Switch the camera on and allow it to settle (1 to 2 hours). Set the camera to an emissivity of 0.99 at a distance of 1m from the container filled with ice and water and to a very narrow temperature range around zero (-5 to +5) [14].

After the camera has settled, fill the container with equal amounts of ice cubes and cold water. Point the camera perpendicularly towards the ice/water surface at a distance of 1m. Stir well. Take a single image of the ice water surface [14].

4.2.2.1 Results of the long-term offset drift test

The average temperature measured during the experiment with the thermal imager after a “cold start” is much higher than the actual temperature of the water which was measured with a thermometer. This can be contributed by the fact the detector has not warmed up, thus producing an inaccurate temperature reading.

The temperature measured with the thermal imager stabilizes after 5 to 10 minutes of use and after 1 hour of continuous use the average temperature measured is lower than the actual water temperature measured with the thermometer. This raises the concern that the detector might be faulty which will lead to temperatures that are captured with the thermal imager after 1 hour of continuous use always being lower than the actual temperature. This will result in misinterpreting fault and inaccurate severity criteria.

4.2.3. Offset variations over observed ranges

Offset variations over observed ranges are the amplification of the camera sensor readout for different temperatures. This effect reveals errors within individual images. Offset variation affects the confidence in the measured temperature.

For this test one needs a container with warm water, at about 40°C, and a precise mercury thermometer. Switch the camera on and allow it to settle (1 to 2 hours). Set the camera to an emissivity of 0.99 at a distance of 1m from the container with warm water and a temperature range between 20°C to 40°C. Maintain this setting throughout the experiment [14].

After the camera has settled, fill a container with 1 to 3 litres of warm water at about 40°C. Stir the water with the thermometer for 1 minute, thus producing a homogeneous temperature distribution throughout the water body and allowing the thermometer to assume the water temperature. Point the camera perpendicularly towards the water surface from a distance of 1m. Take an image and obtain a thermometer reading. Note the image name and thermometer reading. Take images and thermometer readings for every 0.5°C of cooling of the water temperature. Always stir the water well before taking an image/reading. If the cooling process is taking too long, small amounts of cold water may be added to accelerate the process, especially once the temperature is close to or below room temperature [14].

4.2.3.1 Results of the offset variations over observed ranges test

Table 4.1 shows the results obtained during this test.

Table 4.1 Test results for the offset variation over observed ranges

Water temp in °C	Average IR temp in °C	Temp diff in °C	Fault accuracy
40	39.1	0.9	97.75%
39.5	38.5	1	97.47%
39	38.5	0.5	98.72%
38.5	37.8	0.7	98.18%
38	36.8	1.2	96.84%
37.5	36.5	1	97.33%
37	36.3	0.7	98.11%
36.5	36	0.5	98.63%
36	35.3	0.7	98.06%
35.5	34.8	0.7	98.03%
35	34.3	0.7	98.00%
34.5	33.9	0.6	98.26%
34	33.1	0.9	97.35%
33.5	32.8	0.7	97.91%
33	32.5	0.5	98.48%
32.5	31.8	0.7	97.85%
32	31.4	0.6	98.13%

4.2.4. Spatial resolution

The spatial resolution has a very direct influence on measurement results. Spatial resolutions are not only determined by the pixel size, but also by the quality of the optical system and, most importantly, correct image focus. In places where there is a steep temperature gradient, a low spatial resolution will result in incorrect thermal measurements. Low resolution blurs the boundaries between areas of different temperature, making hot parts appear colder and cold parts warmer than they really are.

For this test use a container filled with warm water, at about 40°C. Switch the camera on and allow it to settle (1 to 2 hours). Set the camera to an emissivity of 0.99 at a distance of 1m from the container with warm water and at an appropriate temperature range to include both room and warm water temperatures. Cut a wedge out of cardboard, 10cm long and 1cm wide, as indicated in figure 4.2 [14]

After the camera has settled, stir the container of water with the thermometer for 30 seconds, thus producing a homogeneous temperature distribution throughout the water body and allowing the thermometer to assume the water temperature. Point the camera perpendicularly towards the water surface at a distance of 1m. Place the cardboard wedge over the container. Take an image if you are sure that the camera is focused. Produce cross-sections across the wedge and measure the water temperature. Use the border line case to calculate the spatial resolution [14].

4.2.4.1 Results of the spatial resolution test

In this experiment the thermal imager – wedge distance d1 = 1m. The thermal imager was able to measure an accurate water temperature reading at a cross-section 3.5cm from the wedge tip, as indicated in figure 4.2. From a distance of 1m the thermal imager will be able to resolve the temperature of an object larger than 3.5mm accurately. For smaller objects, the temperature readouts would not be correct. This is calculated as follows:

$$Z = \frac{1cm \times 3.5cm}{10cm} = 3.5mm \qquad [14]$$

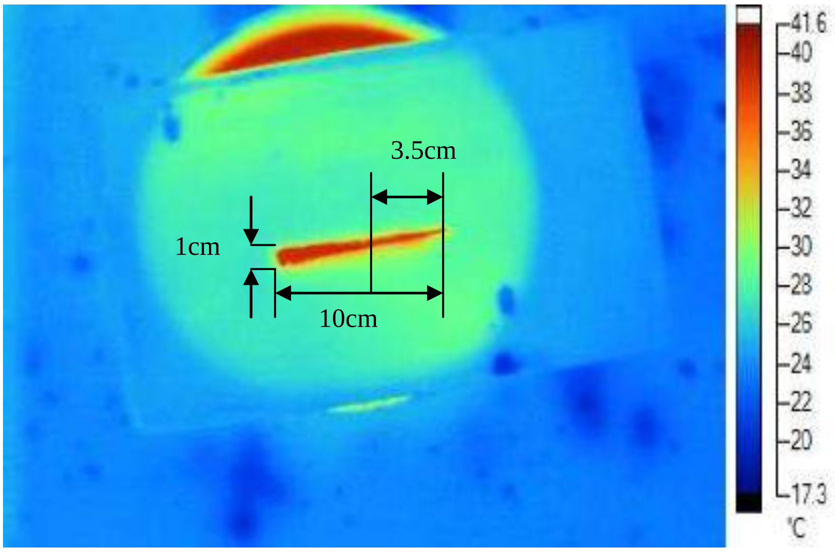


Figure 4.2 Example of wedge

4.2.5. Thermal Flooding

Thermal flooding occurs when a warm object is introduced into the observed scene. Radiation from the warm object “floods” the entire image area, making other objects appear warmer than they are.

For this test one will need one container filled with water at room temperature and one with warm water, at about 40°C. Switch the camera on and allow it to settle (1 to 2 hours). Set the camera to an emissivity of 0.99 at a distance of 1m from the container filed with water and at an appropriate temperature range to include both room and warm water temperatures [14].

After the camera has settled, stir both the containers of water with the thermometer for 1 minute, thus producing a homogeneous temperature distribution throughout the water body and allowing the thermometer to assume the water temperature. Point the camera perpendicularly towards the room temperature water surface at a distance of 1m and take an image. Immediately introduce the warm water into the FOV and take an image containing both containers with water, one at room temperature and the other at about 40°C [14].

4.2.5.1 Results of the thermal flooding test

A 0.1°C reduction in the reference source temperature was detected when a warm object was introduced into the FOV. The results can be seen in figure 4.3. The left image shows only the container filled with water at room temperature in the FOV. The image on the right shows the results just after the container filled with warmer water was introduced into the FOV.

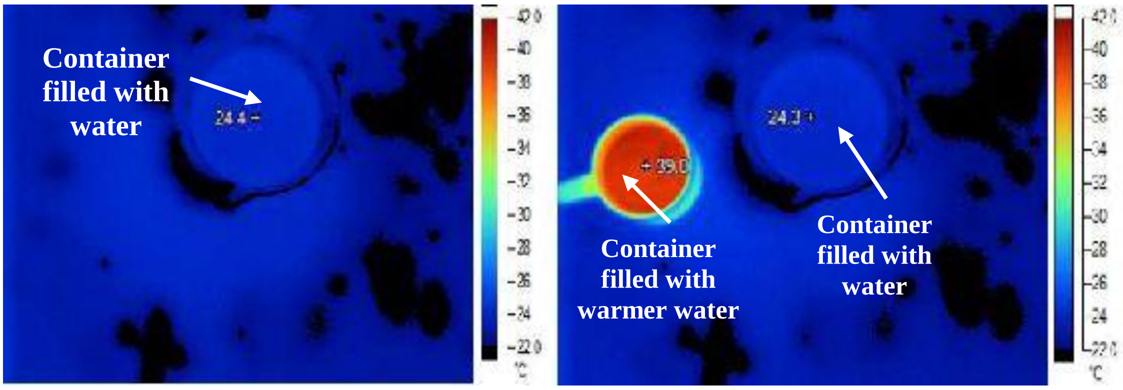


Figure 4.3 Thermal flooding results

4.2.6. Thermal resolution

Thermal resolution is usually expressed by camera manufacturers as the “Noise equivalent temperature difference” (NETD). This is because it is caused by two factors, namely noise and digitization step width. Incorrect spot measurements are a direct result of limited thermal resolution. To avoid this, always use area readouts, e.g. 4 x 4 pixels or 8 x 8 pixels, as prescribed by various international standards such as the British standard (BS) and the international standard organization (ISO).

For this test one will need a container filled with warm water at about 30°C. Switch the camera on and allow it to settle (1 to 2 hours). Set the camera to an emissivity of 0.99 at a distance of 1m from the container filled with water and at an appropriate temperature range [14].

After the camera has settled, stir both the containers of water with the thermometer for 30 seconds, thus producing a homogeneous temperature distribution throughout the water body and allowing the thermometer to assume the water temperature. Point the camera perpendicularly towards the room temperature water surface at a distance of 1m and take an image. Define in the captured image a statistical area of at least 10 x 10 pixels in size and calculate the standard deviation [14].

4.2.6.1 Results of the thermal resolution test

Figure 4.4 illustrates the results obtained during the thermal resolution test. Due to noise the average temperature of the water measured with the thermal imager, is 1.3°C warmer that the actual water temperature measured with the thermometer.

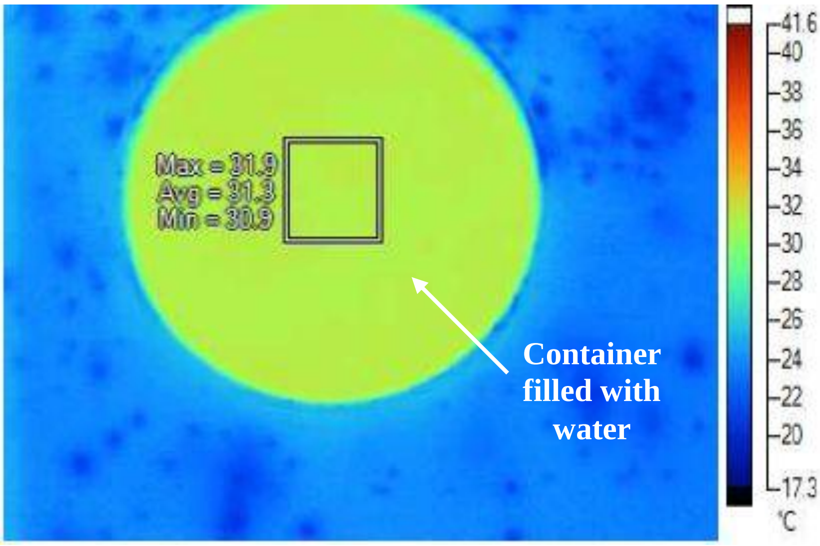


Figure 4.4 Thermal resolution results

4.3. Determining the emissivity of an object

Due to the fact that the exact emissivity of all materials may not be known, an uncomplicated test can be performed to measure the actual value thereof. The following steps were taken to determine the actual emissivity of the heat source to be used in the experiments to follow.

Step 1 - Apply a high emissivity spray or piece of electrician's tape to one half of the heat source and create a uniform background. The emissivity of a good electrician's tape is usually between 0.96 and 0.99 and will be indicated by the manufacturer.

Step 2 - Heat the heat source to about 20°C above ambient.

Step 3 - Measure the object's temperature on the high emissivity spot, the electrician's tape, using an emissivity value appropriate to the spot.

Step 4 - Aim the thermal imager to a spot that is not sprayed with the high emissivity spry or taped with the electrician's tape.

Step 5 - Adjust the thermal imager's emissivity until the measured temperature is equal to that of the reference spot. The thermal imager will then display the true emissivity of the heat source [22].

4.3.1 Results of the emissivity test

The emissivity test reveals that the emissivity of the heat source to be used in the following experiments, is 0.98.

Chapter 5

Methodology

5.1. Introduction

A number of scientific experiments were carried out on test apparatus to improve the understanding of the impact of convection, ambient air temperature and relative humidity on resultant infrared thermal images. Two similar heat sources, simulating a hotspot, at different temperature settings, were used to determine whether the hotspot temperature should also be considered in conjunction with the atmospheric elements. The need for these experiments has also been identified by EPRI (Electrical Power Research Institute) in the USA as necessary to develop international severity criteria.

The accuracy of infrared thermography can be affected by various environmental conditions. This is particularly concerning when establishing severity criteria as in reporting and alarm settings.

5.2. Experiment 1: Effect of wind (convection) on a heat source

5.2.1. Experiment set-up

To test the cooling effect of wind on a hot object, wind at different wind speeds will be directed towards two heat sources at different temperatures. To simulate wind, a pre-designed fan blade is connected to the shaft of a 5.5kW induction motor. Figure 5.1 shows the auto-transformer to which the induction motor is connected for supply.

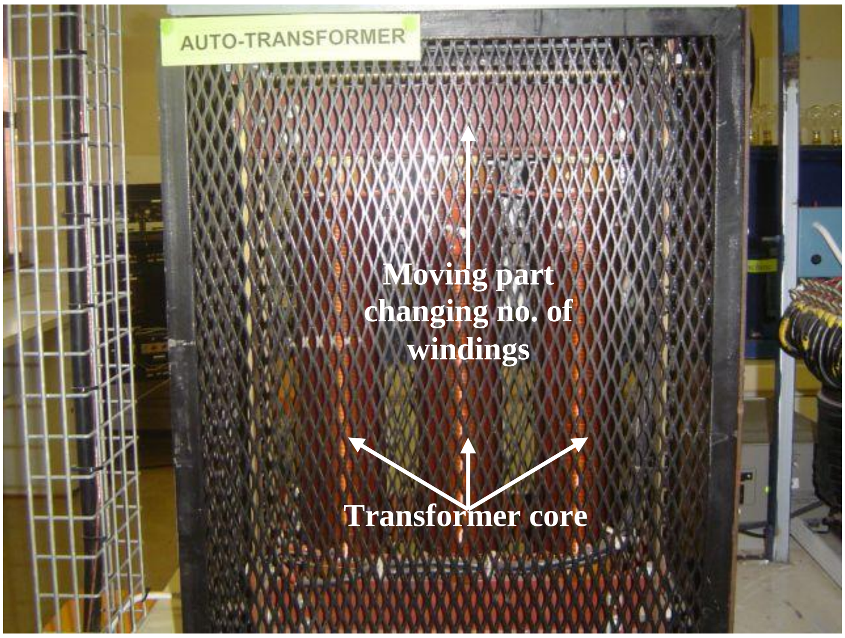


Figure 5.1 Auto-transformer

The auto-transformer has a set wheel at the side that allows changing the number of windings around the core. The number of windings on the primary and the secondary side of the auto-transformer determines the output voltage.

The speed of the fan can be controlled by either changing the frequency or the voltage supplied to the induction motor. For this experiment the input voltage to the induction motor will be varied by means of the auto-transformer. When the output voltage of the auto transformer is increased, the motor speed also increases. The voltage of the auto transformer is set to 0V at the start of the experiment and gradually increased until the desired wind speed has been reached. The increase of wind force generated by the fan blades is measured by means of an anemometer and the temperature and relative humidity by temperature and relative humidity probes. The temperature and relative humidity probes are connected to a micro logger to record this data throughout the duration of the experiment.

The wind generated is forced towards two heat sources at different temperatures placed 2m from the fan blades, forcing the wind perpendicularly towards them. The 2m distance between the heat source and the fan blades allows for sufficient airflow and for the positioning of the anemometer as well as the temperature and relative humidity probes in front of the heat source without the heat source influencing the readings too much. The heat source used in this experiment is an IDEAS double solid hotplate, model IDS250A, 230V – 50Hz 2000W. The one plate is set to its maximum level while the other to ¾ of its maximum level. This will allow for results of different temperature heat sources exposed to the same wind conditions over the same time period. To create the effect of a "wind tunnel", polystyrene is placed on the sides in such a way as to "guide" the wind towards the heat source and reduce turbulence. Ensuring sufficient open space behind the heat sources will also reduce the risk of turbulence. Figure 5.2 is a photo of the set-up during this experiment.

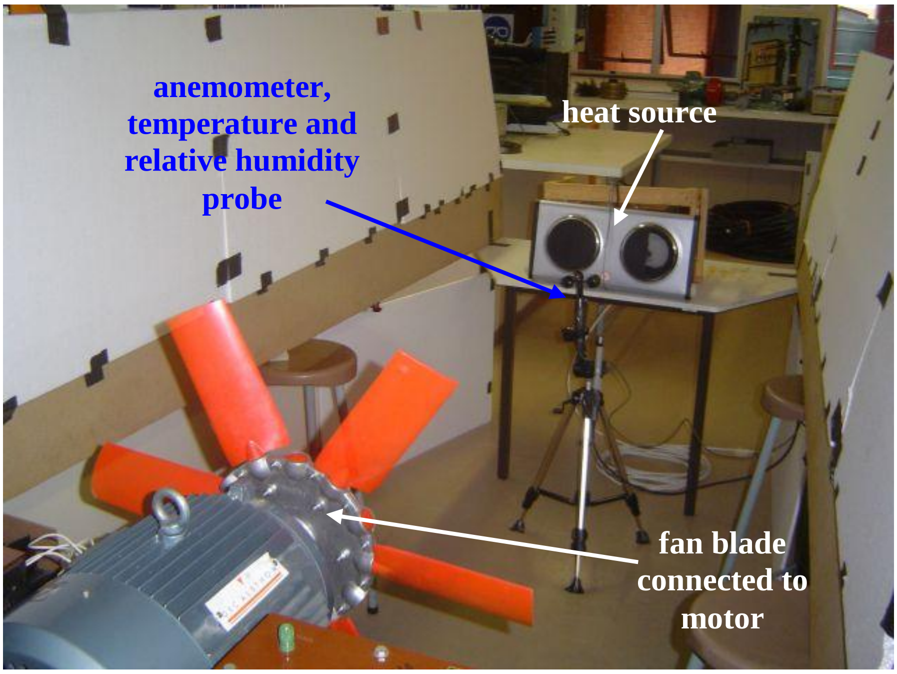


Figure 5.2 Wind effect experiment set-up

The thermal imager should be positioned to allow both the heat sources to be seen through the lens at all times and so that an image can be taken while the motor is running without disturbing the wind. Figure 5.3 shows the set-up from behind the thermal imager. For safety purposes the thermal imager were positioned behind the fan blades. This increased the distance between the thermal imager and the heat source. This distance is within the limits of the thermal imager and the spot size according to the results obtained in the spatial resolution test in 4.2.4

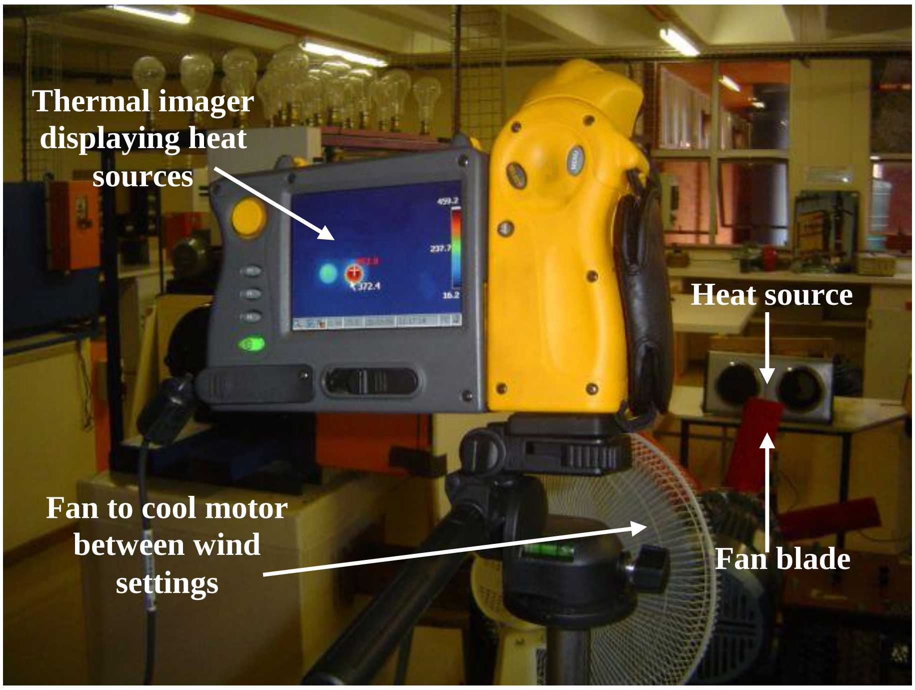


Figure 5.3 Thermal imager position during wind effect experiment

During this experiment it is important to set the focus of the thermal imager before any thermal image is captured and to maintain to this setting throughout the experiment. Different focus settings may lead to different results.

5.2.2. Experimental procedure

Step 1 - Gradually increase the voltage of the auto transformer to increase the wind generated by the fan blades until the desired wind speed is reached. Record the voltage output of the auto-transformer. This value will be used when the experiment is repeated for the second and third times. By using the same voltages for the individual sets, the motor speed will be theoretically the same, resulting in roughly the same wind generated by the fan blades, excluding turbulent flow.

Step 2 - Switch the motor off allowing one of the heat sources to heat to its maximum heat and the other to about ¾ of its maximum heat before beginning the experiment.

Step 3 - Once the set temperatures of the heat sources have been reached, take a reference image of the heat sources without any wind on them.

Step 4 - Start the motor. During this time the micro logger will record the temperature, relative humidity and wind speed every second for the duration of the test.

Step 5 - Without interrupting the wind at the set speed, take a thermal image of both heat sources after every minute for up to 10 minutes.

Step 6 - After the 10th minute has elapsed, increase the voltage to the new wind speed. Increase the wind speed in increments of 5km/h, starting with a wind speed of 5km/h and going up to 30km/h.

Step 7 - Switch the motor off to allow the heat sources to recover and reach their respective maximum temperature values.

Step 8 – Repeat steps 1 to 7

Step 9 - Repeat steps 1 to 7 for a third time.

From the recorded data obtained with the micro logger, calculate the average wind speed for each minute during the test. Use these per minute averages to calculate the average wind speed to which the heat sources were exposed to over the 10 minutes for each wind setting. These average wind speeds must be calculated separately for the three individual repeats. The average wind speed between the three repeats will then be used to formulate the conclusion.

The same method of calculating the average heat source temperature and energy was used as with the wind calculations.

5.3. Experiment 2: Effect of air temperature on a heat source

Due to the close relationship between ambient air and relative humidity it is impossible to test these two climatic elements independently of each other. The one is dependent on the other [15]. Because of to the natural relationship between these two elements it is possible to change the humidity, to a certain extent, at high air temperatures, but this relationship is fixed to the natural outcome at low air temperatures. During this experiment the relative humidity must be held as constant as possible and the air temperature will be changed.

5.3.1. Experimental set-up

For this experiment an IDEAS double solid hotplate, model IDS250A, 230V – 50Hz 2000W, is used as the heat source, and it will be placed inside a climate controlled cabinet in order to expose it to the set ambient temperature and relative humidity. The climate controlled cabinet's dimensions are 2.7m x 1.5m x 2m. Inside the cabinet the air temperature and the relative humidity, to a certain extent, will be electronically controlled using logarithms programmed into the software of the cabinet.

The climate controlled cabinet's temperature and relative humidity are controlled by a central computer. The software used by the central computer to control the climate inside the cabinet is programmed by Prof Koos Terblans from the Department of Physics at the

University of the Free State (UFS). Once the desired air temperature and relative humidity have been punched into the software, this information from the micro-controller is sent to the micro-controller by means of a duplex RS232 communication system. A PID formula controls the temperature inside the cabinet.

5.3.2. Experimental procedure

For this experiment one of the heat sources will be set to its maximum temperature and the other to ¾ of its maximum rating. This will allow for testing of the influence of constant relative humidity and varying air temperature on a hotspot and determine whether the hotspot temperature should also by accounted for when setting the severity criteria.

The climate controlled cabinet’s temperature will be set at 5°C to start with and increased with 5°C intervals every hour up to 30°C. The relative humidity will be set at 60% for all temperatures during the experiment. This sequence will simulate the temperature rise during a typical summer’s day. When the desired air temperature and relative humidity inside the climate controlled cabinet are reached, the hotspots will be exposed to the new temperature for one hour before any thermal image is taken thereof. During this hour, the program logs the temperature and relative humidity inside the cabinet every 10 minutes. This log file will be used to determine the average air temperature and relative humidity to which the heat sources were exposed during that specific hour. The values obtained with air temperature at 5°C will be used as the reference data.

The heat sources will be switched on and allowed to heat to their respective maximum temperatures and remain there for the duration of the experiment. When the desired air temperature inside the cabinet is reached, and the heat sources are exposed to it for one hour, a thermal image is taken of the two heat sources separately. The air temperature will be increased by 5°C and the same process as explained above will be followed for the new air temperature.

From the log file data, the average air temperature inside the climate controlled cabinet to which the heat sources were exposed during the hour-long experiment for each ambient air temperature setting is calculated. This must be calculated separately for the three individual repeats. The average ambient air temperature between the three repeats will be used to formulate the conclusion.

The same method of calculating the average heat source temperature and energy will be used as with the ambient air temperature inside the climate controlled cabinet.

5.4. Experiment 3: Effect of relative humidity on a heat source

Due to the close relationship between ambient air temperature and relative humidity, it is impossible to test these two climatic elements independently of each other, as the one is dependent on the other [15]. Because of the natural relationship between these two elements it is possible to change the humidity, to a certain extent, at high air temperatures, but that is fixed to the natural outcome at low air temperatures. This is due to air having more energy at high air temperatures than at low air temperatures. During this experiment the air temperature will be set to a constant 25°C, while the relative humidity will be changed between 50% and 65%. The heat sources will be exposed to the different relative humidities for 30 minutes before temperature readings are taken with the thermal imager.

5.4.1. Experimental set-up

For this experiment an IDEAS double solid hotplate, model IDS250A, 230V – 50Hz 2000W, is used as the heat source, which will be placed inside a climate controlled cabinet in order to expose it to the set ambient temperature and relative humidity. The climate controlled cabinet's dimensions are 2.7m x 1.5m x 2m. Inside the cabinet the air temperature and the relative humidity will be electronically controlled using logarithms programmed into the software of the cabinet. Once the desired air temperature and relative humidity have been punched into the software, this information is sent to the micro-controller by means of a duplex RS232 communication system. A PID formula controls the temperature inside the cabinet. The relative humidity is not isolated in the cabinet, but also depends upon the relative humidity of the surrounding air.

5.4.2. Experimental procedure

For this experiment one of the heat sources will be set to its maximum temperature while the other to ¾ of its maximum rating. This will allow for testing the influence of changing relative humidity at a constant air temperature on a hotspot and determine whether the hotspot temperature should also by accounted for when setting the severity criteria.

The climate controlled cabinet's temperature will be set at 25°C and will remain as such throughout the experiment. The relative humidity will be set at 50% and increased with 5% intervals up to 65%. When the desired relative humidity inside the cabinet is reached, and the heat sources are exposed to it for 30 minutes, a thermal image is taken of the two heat sources separately. During this time, the program logs the temperature and relative humidity inside the cabinet every minute. This log file will be used to determine the average air temperature and relative humidity during that specific 30 minute period to which the heat sources were exposed. The values obtained with air temperature at 25°C and relative humidity at 50% will be used as the reference data.

The heat sources will be switched on and allowed to heat to their respective maximum temperatures and remain there for the duration of the experiment. When the desired air temperature and relative humidity inside the cabinet are reached, and the heat sources exposed to this for 30 minutes, a thermal image is taken of the two heat sources separately. The air temperature will remain at 25°C while the relative humidity will be increased by 5% and the same process as explained above will be followed for the new relative humidity setting.

From the log file data, the average air temperature and relative humidity inside the climate controlled cabinet to which the heat sources were exposed during the 30 minute long experiment for each relative humidity setting, are calculated. This must be calculated separately for the three individual repeats. The average ambient air temperature and relative humidity between the three repeats will be used to formulate the conclusion.

The same method of calculating the average heat source temperature and energy will be used as for the ambient air temperature and relative humidity inside the climate controlled cabinet.

Chapter 6

Results

6.1. Introduction

The results obtained during the three experiments highlighted the influenced of climatic elements on the detection of hotspots. Trends were observed but need more detailed testing to formulate a correction factor for each of the climatic elements or a combination of them. The hotspot temperature is an important factor that also needs to be considered when determining the severity of a problem.

The rate at which an object radiates energy is proportional to the fourth power of the Kelvin temperature scale [23]. The energy of the heat source will determine how it will be influenced by the climatic elements. Less energy means less resistance to retaining its temperature.

The transfer of heat will continue as long as there is a difference in temperature between two locations. Once the two locations have reached the same temperatures, thermal equilibrium is established and the heat transfer stops. The rate that the temperature of an object changes, is proportional to the rate the heat is transferred to or away from that object.

6.2. Experiment 1: Effect of wind (convection) on a heat source

Table 6.1 is a summarized account of the average results that were obtained from the three reruns of the experiment at different wind speeds. Due to instability in the wind speed readings during the experiment, each test was repeated three times in order to calculate average values. The instability of the wind speed is mainly due to friction and turbulence that could not have been overcome by the polystyrene panels and also because of the wind blowing onto a vertical flat surface. The values obtained during the three separate tests show no significant difference between the different reruns. The reference temperature for both the heat sources was the highest temperature measured with the thermal imager for each of the heat sources when there was no wind blowing on them. The average wind speed, average air temperature and average relative humidity are calculated by using the recorded per minute data registered by the micro-logger during the experiment. Both the air temperature and the relative humidity were constant during the course of the experiment and were not taken into account when formulating a conclusion.

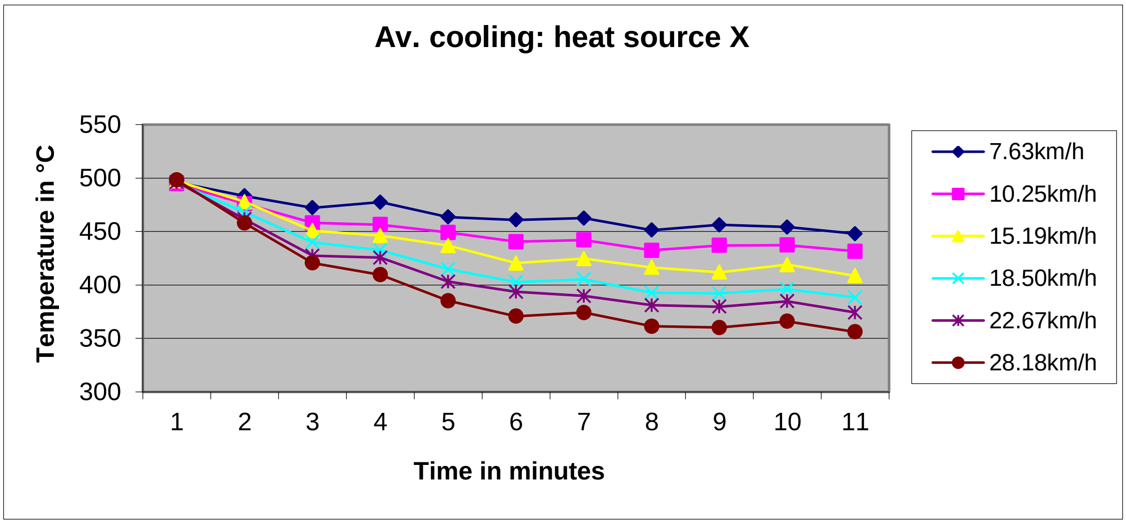
Table 6.1 Test results for wind experiment

	Wind speed in km/h	**T at 0 minutes in °C**	**T at 10 minutes in °C**	**% T loss**	**Q at 0 minutes in Watts**	**Q at 10 minutes in Watts**	**% Q loss**
Heat source X	7.63	496.00	447.90	**9.69%**	3438.83	2655.86	**22.77%**
Heat source Y		248.00	210.47	**15.22%**	726.02	537.24	**26.00%**
Heat source X	10.25	494.53	431.20	**12.75%**	3412.67	2421.85	**29.03%**
Heat source Y		253.13	199.40	**15.38%**	655.57	486.96	**25.72%**
Heat source X	15.19	497.30	418.90	**17.85%**	3462.15	2121.55	**38.72%**
Heat source Y		251.27	186.17	**26.18%**	742.87	433.06	**41.70%**
Heat source X	18.50	495.40	396.10	**21.65%**	3428.11	1879.10	**45.19%**
Heat source Y		243.93	178.80	**26.39%**	702.17	412.15	**41.30%**
Heat source X	22.67	496.17	384.63	**24.61%**	3441.82	1723.86	**49.91%**
Heat source Y		243.27	172.50	**30.20%**	698.56	378.15	**45.87%**
Heat source X	28.18	498.17	365.93	**28.54%**	3477.75	1539.25	**55.74%**
Heat source Y		252.10	167.77	**35.27%**	747.61	355.78	**52.41%**

In table 6.1:

- “T at 0 min” represents the measured reference temperature of the heat sources without any wind.
- “T at 10 min” represents the measured temperature of the heat sources after they were exposed to the specific wind for 10 minutes.
- “% T loss” is the temperature loss between the reference temperature and the measured temperature after 10 minutes expressed as a percentage.
- “Q at 0 min” represents the calculated energy radiated by the surface of the heat sources without any wind. This was used as the reference energy radiated by the heat source.
- “Q at 10 min” represents the calculated energy radiated by the surface of the heat sources after they were exposed to the specific wind for 10 minutes.
- Q is calculated using equation 3.10.
- “% Q loss” is the loss in energy radiated between the reference energy and the calculated energy after 10 minutes, expressed as a percentage.

The summarized results of table 6.1 can also be expressed as graphs. This can be seen in more detail in graph 6.1 to graph 6.6. Graph 6.1 shows the temperature loss of the hotter heat source (heat source X) when it is exposed to the different average wind speeds for 10 minutes.

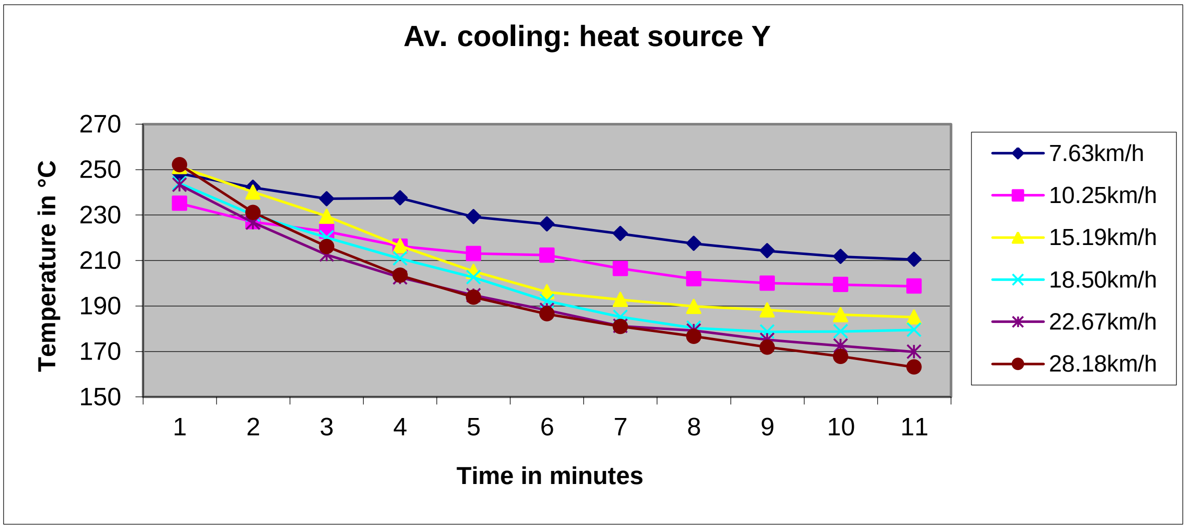


Graph 6.1 Temperature loss of heat source X at various wind speeds

On closer inspection of graph 6.1 the following can be seen:

- More heat is lost by the heat source with an increase in wind speed.
- A sudden large temperature loss occurs in the first 3 to 4 minutes of exposure after which it eases off and loses heat more gradually. This behaviour is true for all wind speeds during the experiment.
- The temperature loss shows an almost linear increase between wind speeds. This is due to the increase of moving molecules transferring heat away from the heated object.

Graph 6.2 shows the temperature loss of the colder heat source (heat source Y) when it is exposed to the same average wind speeds for 10 minutes, as was heat source X.



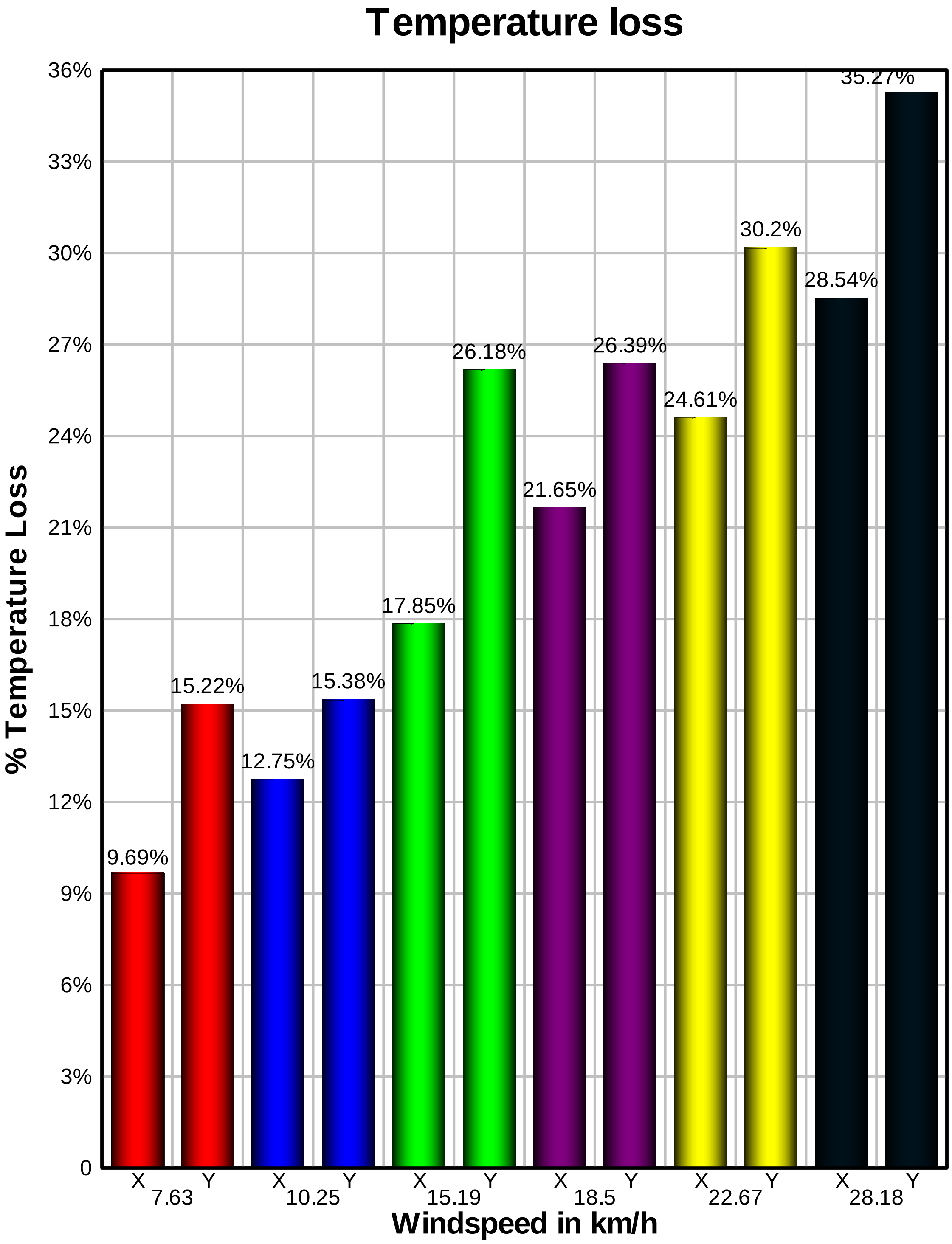
Graph 6.2 Temperature loss of heat source Y at various wind speeds

On closer inspection of graph 6.2 the following can be seen:

- More heat is lost by the heat source with an increase in wind speed.
- The temperature loss is more constant than that of heat source X. From the 1st minute there is an even percentage temperature loss, irrespective of the wind speed.

When the different results were compared between heat source X and heat source Y, it was discovered that although heat source X loses more of its temperature, °C, than does heat source Y over the tested time period when exposed to the same wind conditions, heat source Y loses more heat when expressed as a percentage than does to heat source X. This value becomes greater as the wind speed is increased.

Graph 6.3 summarizes the percentage of temperature loss for each heat source per wind speed over the tested 10 minute period.



Graph 6.3 Summarized percentage of temperature loss

The two bars, of similar colour, represent heat source X and heat source Y. The first bar of a particular colour represents heat source X and the second heat source Y. The results of both heat source X and heat source Y are represented on the same graph; this is to emphasize the importance of the heat source temperature when setting severity criteria.

When the temperature loss is calculated for a given heat source, heat source Y loses more heat (temperature), expressed as a percentage, per wind speed than does heat source X when it is exposed to the same wind conditions over the same time period. The biggest difference occurred at an average wind speed of 15.19km/h and the smallest at 10.25km/h.

The second part of this experiment focused on the radiated energy loss by the two heat sources, at different temperatures, when exposed to the same wind conditions for the same time period. Energy loss in this section refers to the transfer of energy from the heat source to the surrounding air due to the increase of moving molecules transferring heat away from the heated object. The rate at which the heat source radiates energy can be calculated with the aid of equation 3.10:

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A T^4 \qquad (3.10)$$

Where:

ε = 0.98 as tested with the emissivity test explained in section 4.3

σ = 5.67 x 10^{-8} W/m^{2}K^4 (Stefan-Boltzmann constant)

Area of the heat source to be:

$$A = \pi r^2 \qquad (5.1)$$

$$A = \pi (0.075)^2$$

$$A = 0.177 m^2$$

Q for the reference temperature of heat source X at 7.63km/h wind speed is calculated as follows:

$$\frac{\Delta Q}{\Delta t} = \varepsilon\sigma A T^4$$

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \times 10^{-8})(0.177)(769)^4$$

=3 438.83W

Q of heat source X at 7.63km/h wind speed after 10 minutes is calculated as follows:

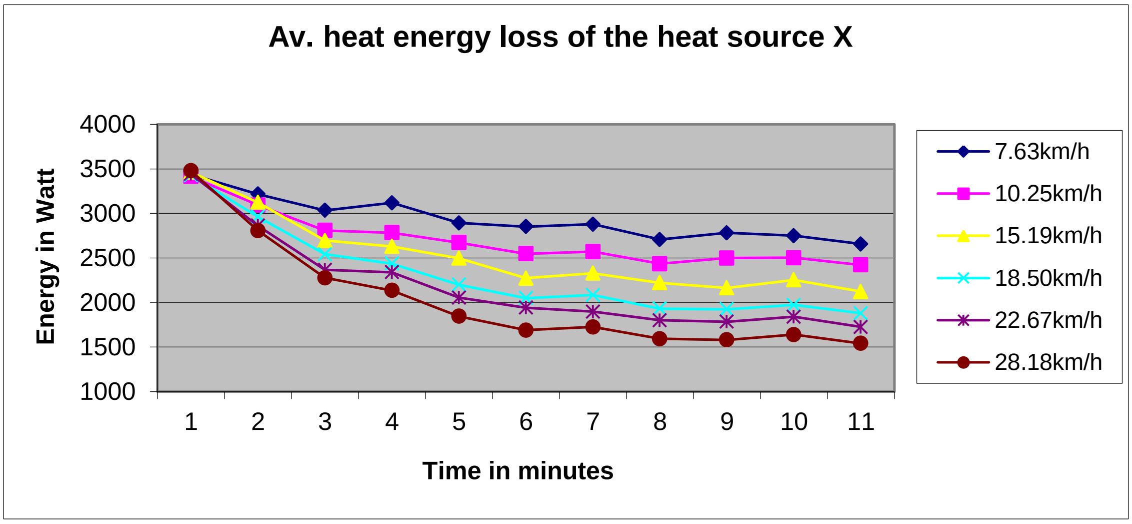
$$\frac{\Delta Q}{\Delta t} = \varepsilon\sigma A T^4$$

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \times 10^{-8})(0.177)(720.9)^4$$

=2 655.86W

The energy loss is then calculated by subtracting the energy radiated by the heat source after it was exposed to a specific wind speed for 10 minutes, from the reference energy radiated with no wind present.

Graph 6.4 illustrates the average heat energy loss of heat source X during the tested time when exposed to the various wind speeds.

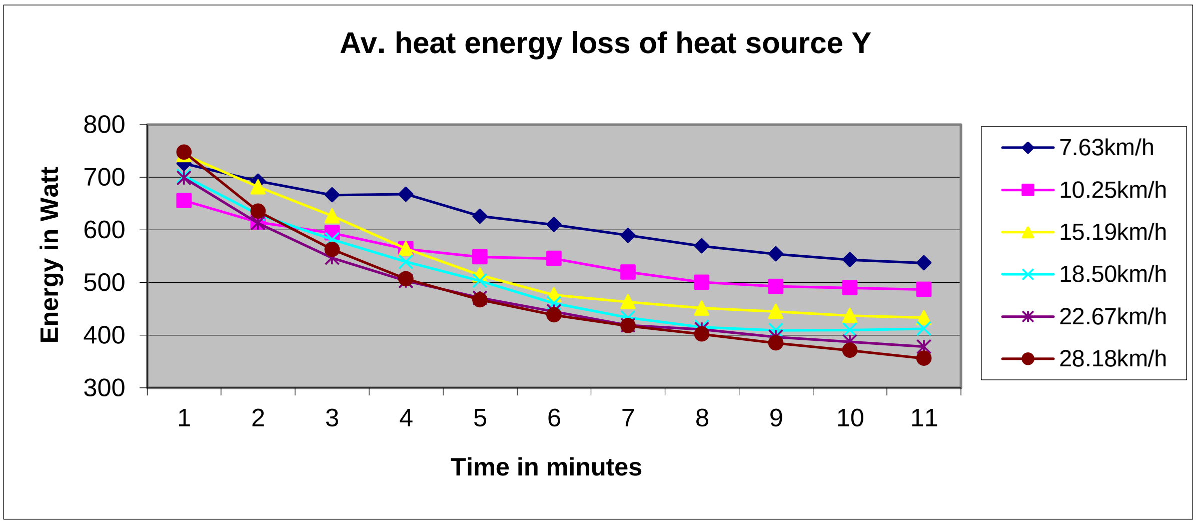


Graph 6.4 Average heat energy loss of heat source X

On closer inspection of graph 6.4 the following can be seen:

- More heat energy is transferred to the surrounding air from the heat source with an increase in wind speed.
- The largest energy transfer occurred in the first 3 to 4 minutes of exposure after which the transfer rate is more gradual. This behaviour is true for all wind speeds used during the experiment.

Graph 6.5 shows the average heat energy loss of heat source Y when it is exposed to the various average wind speeds for 10 minutes.



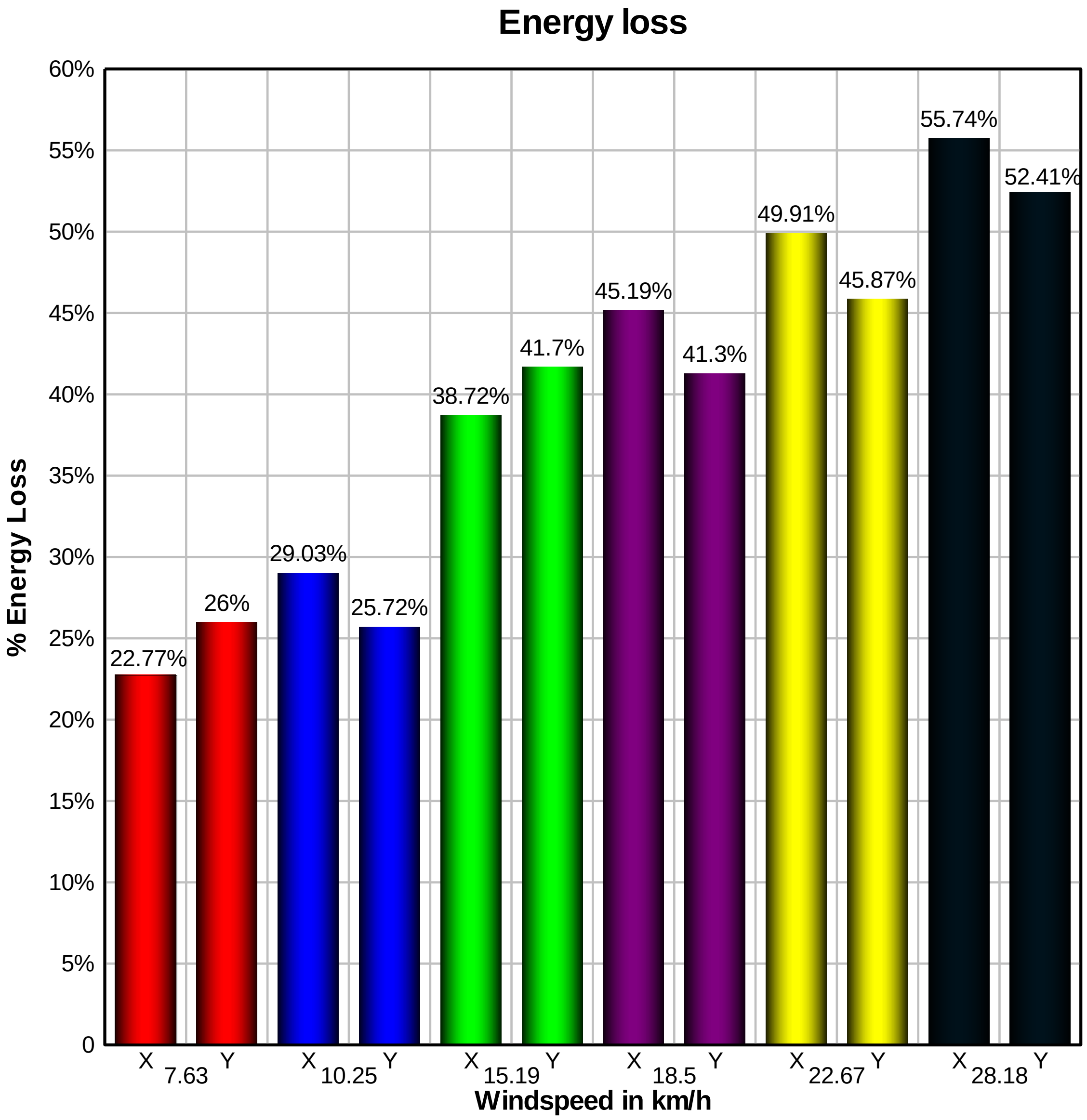
Graph 6.5 Average heat energy loss of heat source Y

On closer inspection of graph 6.5 the following can be seen:

- More heat energy is transferred to the surrounding air from the heat source with an increase in wind speed.
- The average heat energy loss is more constant than that of heat source X, resulting in a more constant transfer rate.

- The difference in reference temperature is due to the thermostats not switching at the same time for heat source X and heat source Y.

Graph 6.6 summarizes the percentage of heat energy loss for each heat source per wind speed over the tested 10 minute period.



Graph 6.6 Summarized percentage of heat energy loss

The two bars, of similar colour, each represent heat source X and heat source Y. The first bar of a particular colour represents heat source X and the second heat source Y. The results of both heat source X and heat source Y are represented on the same graph; this is to emphasize the importance of the heat source temperature when setting severity criteria.

The energy transfer during this experiment is directly proportional to the average wind speed. Although heat source X loses more energy per wind speed than does heat source Y, the percentage of energy loss is almost the same, viz. only a 3% to 4% difference between the two irrespective of their temperatures.

6.3. Experiment 2: Effect of air temperature on a heat source

Table 6.2 is a summarized account of the average data collected during this experiment. To increase accuracy each test was repeated three times. The values obtained during the three separate tests shown no significant difference between the different reruns. Both the heat source's measured temperatures decrease with a rise in the surrounding air temperature, resulting in the energy radiated also decreasing as the air temperature rises. This is due to the energy transfer between the heat source and the surrounding air. The rate at which the transfer occurs is neither uniform nor predictable but is dependent on the fourth power of the Kelven scale of the heat source temperature and the surrounding air temperature.

Table 6.2 Summarized test results for air temperature experiment

	Av. air temp in °C	Av. RH in %	Heat source temp in °C	Energy of heat source in Watts	Energy of Surroundings in Watts	Energy loss from previous temp in Watts	Energy without transfer in Watts	No transfer - surrounding energy in Watts
Heat source X	4.95	61.94	480.40	3168.39	3109.70			
Heat source Y			321.90	1231.69	1173.00			
Heat source X	9.44	61.31	468.43	2971.73	2909.16	196.66	3105.59	196.44
Heat source Y			310.07	1136.67	1074.10	95.02	1169.06	94.96
Heat source X	14.65	60.67	458.33	2813.74	2746.41	157.99	2904.30	157.89
Heat source Y			294.50	1020.31	952.98	116.36	1069.20	116.22
Heat source X	19.51	59.54	443.93	2597.95	2525.96	215.79	2741.00	215.04
Heat source Y			280.20	921.31	849.33	98.99	947.94	98.61
Heat source X	24.08	51.76	436.33	2489.58	2412.98	108.37	2521.29	108.31
Heat source Y			266.57	833.93	757.33	87.39	844.35	87.02
Heat source X	29.07	40.59	427.97	2374.34	2292.48	115.23	2407.60	115.13
Heat source Y			255.30	766.14	684.27	67.79	751.59	67.33

In table 6.2, the headings represent the following:

- "Av. air temp" is the average air temperature measured in °C inside the climate controlled cabinet, to which the heat sources were exposed for 1 hour.
- "Av. RH" is the average relative humidity measured in % inside the climate controlled cabinet, to which the heat sources were exposed for 1 hour.
- "Heat source temp" is the temperature measured with the thermal imager of the heat source after it was exposed to the indicated air temperature for 1 hour.
- "Energy of heat source" is the heat energy calculated using equation 3.10 where T is the measured temperature of the heat source.

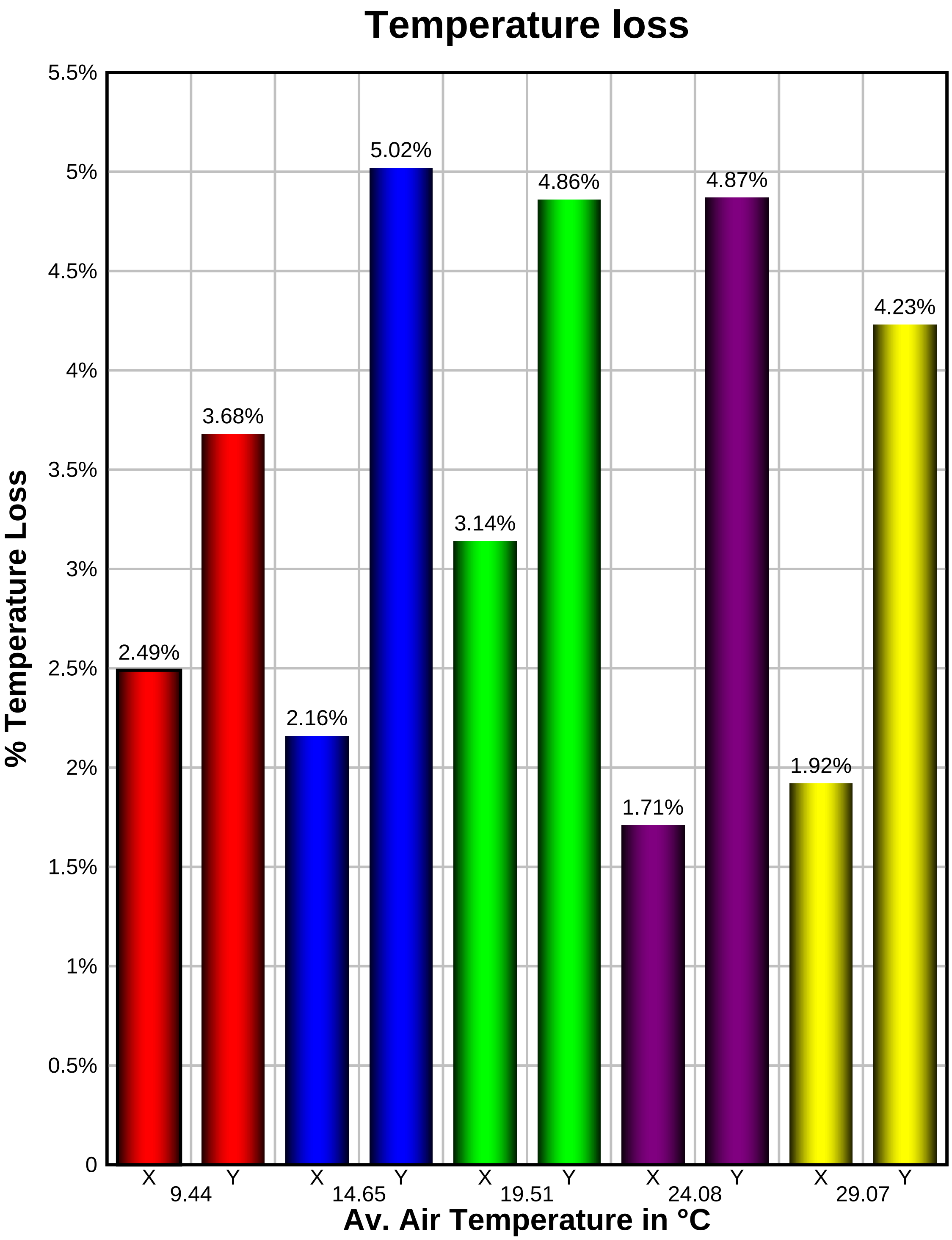
- “Energy of surroundings” is the heat energy calculated using equation 3.10 where T is the air temperature inside the climate controlled cabinet.
- “Energy loss from previous temp” is the reduction in heat energy from the previous reading.
- “Energy without transfer” is the heat energy calculated if no energy transfer was present by using equation 3.10.
- “No transfer – surrounding energy” is the heat energy calculated by subtracting the value obtained in “Energy without transfer” from the value obtained in “Energy of surroundings”.

Table 6.3 Percentages of temperature and energy loss

Heat source X		**Heat source X**	
Temp loss from 4.95°C - 9.44°C	2.49%	Energy loss from 4.95°C - 9.44°C	6.21%
Temp loss from 9.44°C - 14.65°C	2.16%	Energy loss from 9.44°C - 14.65°C	5.32%
Temp loss from 14.65°C - 19.51°C	3.14%	Energy loss from 14.65°C - 19.51°C	7.67%
Temp loss from 19.51°C - 24.08°C	1.71%	Energy loss from 19.51°C - 24.08°C	4.17%
Temp loss from 24.08°C - 29.07°C	1.92%	Energy loss from 24.08°C - 29.07°C	4.63%
Heat source Y		**Heat source Y**	
Temp loss from 4.95°C - 9.44°C	3.68%	Energy loss from 4.95°C - 9.44°C	7.71%
Temp loss from 9.44°C - 14.65°C	5.02%	Energy loss from 9.44°C - 14.65°C	10.24%
Temp loss from 14.65°C - 19.51°C	4.86%	Energy loss from 14.65°C - 19.51°C	9.70%
Temp loss from 19.51°C - 24.08°C	4.87%	Energy loss from 19.51°C - 24.08°C	9.49%
Temp loss from 24.08°C - 29.07°C	4.23%	Energy loss from 24.08°C - 29.07°C	8.13%

Table 6.3 represents the percentages of loss in temperature as well as energy when the air temperature was increased for both heat source X and heat source Y. The measured percentage of temperature loss calculated between air temperature settings varies between 1.71% and 3.14% for heat source X, and 3.68% and 5.02% for heat source Y. This indicates that heat source Y, similar to convection, loses more of its measured temperature expressed as a percentage when exposed to the same air temperature as heat source X. The biggest percentage of loss of the measured temperature is recorded between 14.65°C and 19.51°C air temperature, 3.14%, for heat source X, and between

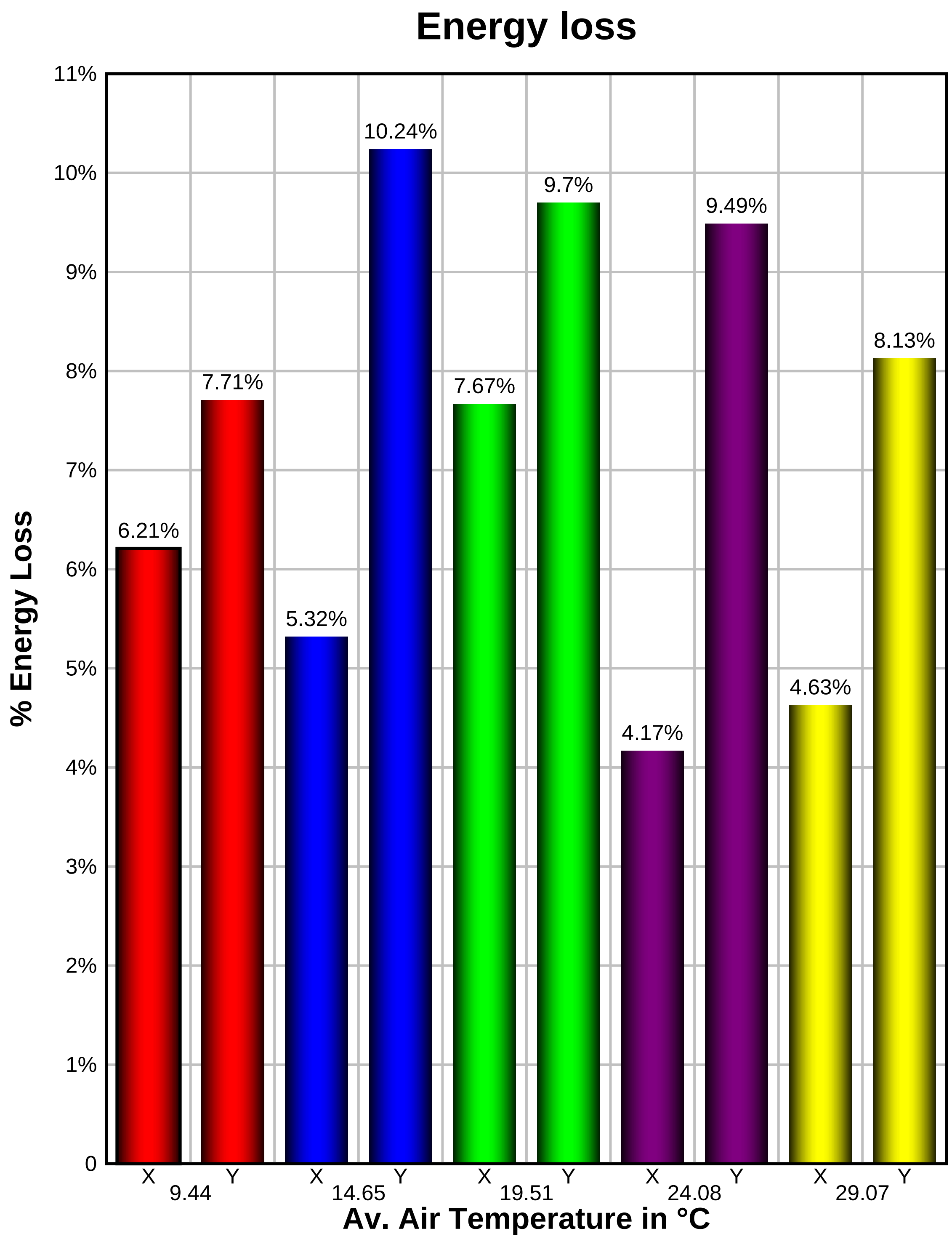
9.44°C and 14.65°C air temperature, 5.02% for heat source Y. These results can be seen in graph 6.7



Graph 6.7 Summarized percentage of measured temperature loss

The two bars, of similar colour, each represent heat source X and heat source Y. The first bar of a particular colour represents heat source X and the second heat source Y. The results of both heat source X and heat source Y are represented on the same graph; this is to emphasize the importance of the heat source temperature when setting severity criteria.

When calculating the energy loss, heat source X loses between 4.17% and 7.67% and heat source Y between 8.13% and 10.24% of its energy within the experimented temperature ranges. These results can be seen in graph 6.8.



Graph 6.8 Summarized percentage of heat energy loss

The two bars, of similar colour, each represent heat source X and heat source Y. The first bar of a particular colour represents heat source X and the second heat source Y. The results of both heat source X and heat source Y are represented on the same graph; this is to emphasize the importance of the heat source temperature when setting severity criteria.

The second law of thermodynamics asserts that, in a closed system, the net flow of heat energy is always from warmer to cooler regions, unless work is done to move it in the other direction. In this experiment the mechanism is radiation, from the heat source to the surrounding air. The amount of energy radiated by the heat source can be calculated using equation 3.10,

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A T^4 \qquad (3.10)$$

The amount of energy loss to the surroundings can be calculated with

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A \left(T_1^4 - T_2^4 \right) \qquad (3.11)$$

Subtracting the radiated energy of heat source X, at 9.44°C, from that at 4.95°C air temperature, reveals an energy transfer from heat source X to the surrounding air of 196.66W. This means that heat source X transferred 196.66W of its energy to the surroundings when the air temperature changed from 4.95°C to 9.44°C during the tested period.

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \text{ x} 10^{-8})(0.177)(753.4)^4$$

= 3 168.39W (energy of heat source X radiated at 4.95°C)

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \text{ x} 10^{-8})(0.177)(741.43)^4$$

= 2 971.73W (energy of heat source X radiated at 9.44°C)

Thus, Total energy transfer = 3 168.39 – 2 971.73

= 196.66W

If we use equation 3.12 with T_1 as the measured heat source temperature at 4.95°C and T_2 air temperature of 9.44°C, find that the heat source is supposed to radiate 3 105.595W of its energy at an air temperature of 9.44°C if there is no energy transfer present. The air will have energy of 2 909.16W at 9.44°C, calculated with equation 3.10. By subtracting the energy of the surrounding air from the energy the heat source is supposed to radiate at 9.44°C, one gets a difference of 196.44W.

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67\ \mathrm{x}\, 10^{-8})(0.177)((753.4)^4 - (282.44)^4)$$

$$= 3\ 105.95\mathrm{W}$$

Thus $$= 3\ 105.595 - 2\ 909.16$$

$$= 196.44\mathrm{W}$$

The above formula proves the existence of energy transfer between a heated object and the surrounding air.

6.4. Experiment 3: Effect of relative humidity on a heat source

Table 6.4 is a summarized account of the average data collected during this experiment. To increase accuracy each test was repeated three times. The values obtained during the three separate tests are in line with each other. No significant difference was measured between the different sets, adding more credibility to the results. With an increase in relative humidity from 50.2% to 54.92% both the heat sources measured temperature gets lower with a rise in relative humidity while the surrounding air temperature remain fairly constant. Resulting in the energy radiated also to decrease as the relative humidity rises. This is due to the energy transfer between the heat source and the surrounding air. The rate at which the transfer occurs is depended on the fourth power of the Kelven scale of the heat source temperature and the surrounding air temperature. With a further increase in relative humidity from 54.92% to 59.93% and again to 63.80%, a reversal of the energy transfer took place. Instead of the heat sources transferring energy to the surrounding air, the surrounding air transferred some of its energy to the heat sources.

Table 6.4 Summarized test results for relative humidity experiment

	Avg air temp in °C	Avg RH in %	Heat source temp in °C	Energy of heat source in Watts	Energy of Suroundings in Watts	Energy loss from previos temperature in Watts	Energy without transfer in Watts	No transfer - surrounding energy in Watts
Heat source X	25.34	50.20	403.30	2057.21	1979.31			
Heat source Y			210.77	538.61	460.71			
Heat source X	25.25	54.92	403.23	2056.33	1978.52	0.88	1979.33	0.81
Heat source Y			210.43	537.10	459.29	1.51	460.77	1.48
Heat source X	25.28	59.93	403.33	2057.60	1979.75	-1.27	1978.48	-1.27
Heat source Y			211.40	541.43	463.59	-4.33	459.25	-4.33
Heat source X	25.50	63.80	403.80	2063.23	1985.16	-5.63	1979.47	-5.69
Heat source Y			213.37	550.25	472.18	-8.82	463.33	-8.85

In table 6.4, the headings represent the following:

- “Av. air temp” is the average air temperature measured in °C inside the climate controlled cabinet to which the heat sources were exposed for 30 minutes.
- “Av. RH” is the average relative humidity measured in % inside the climate controlled cabinet to which the heat sources were exposed for 30 minutes.
- “Heat source temp” is the temperature measured with the thermal imager of the heat source after it was exposed to the indicated air temperature and relative humidity for 30 minutes.
- “Energy of heat source” is the heat energy calculated using equation 3.10 where T is the measured temperature of the heat source.

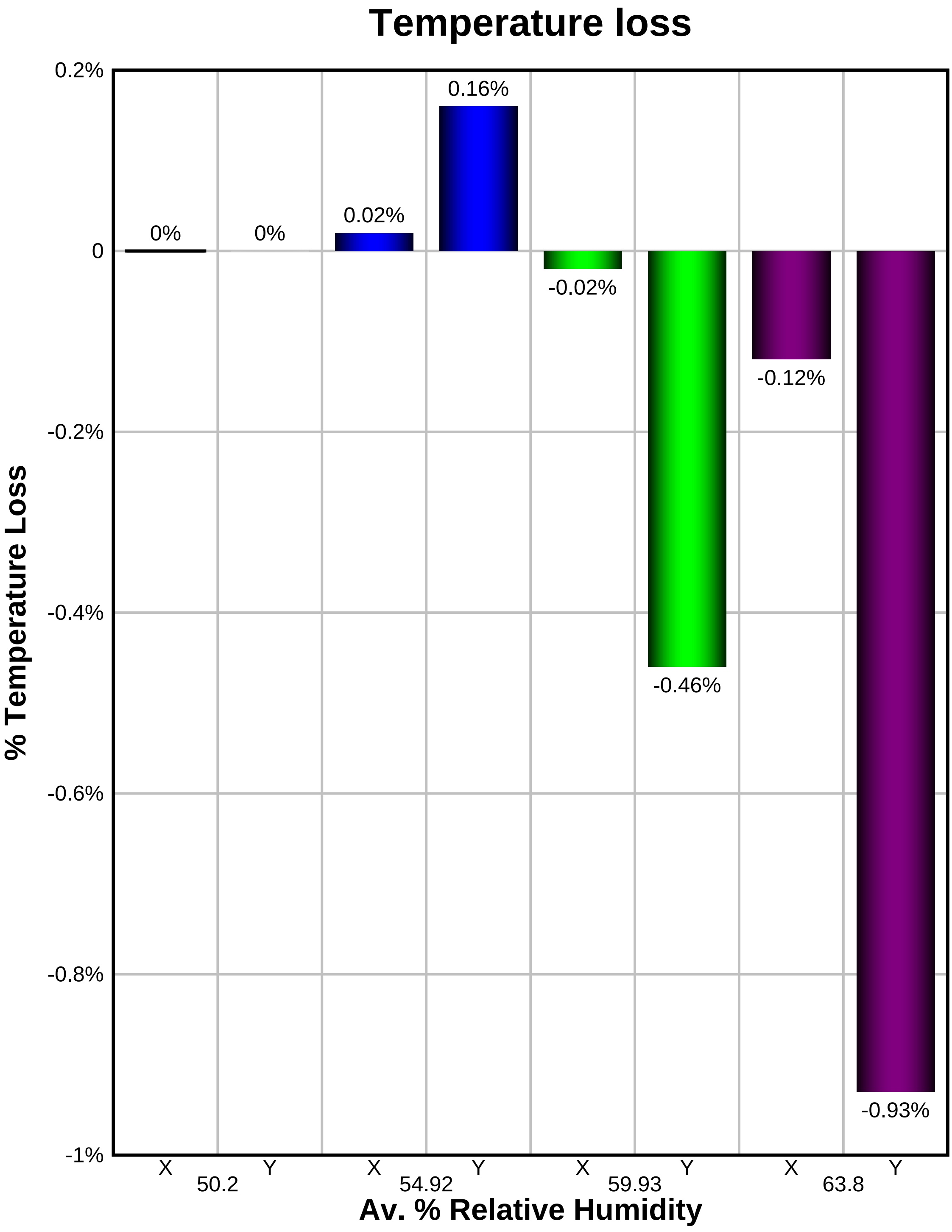
- “Energy of surroundings” is the heat energy calculated using equation 3.10 where T is the air temperature inside the climate controlled cabinet.
- “Energy loss from previous RH” is the reduction/gain in heat energy from the previous reading.
- “Energy without transfer” is the heat energy calculated if no energy transfer were present when using equation 3.10.
- “No transfer – surrounding energy” is the heat energy calculated by subtracting the value obtained in “Energy without transfer” from the value obtained in “Energy of surroundings”.

Table 6.5 Percentages of temperature and energy loss

Heat source X		**Heat source X**	
Temp loss from 50.2% - 54.92%	0.02%	Energy loss from 50.2% - 54.92%	0.04%
Temp loss from 54.92% - 59.93%	-0.02%	Energy loss from 54.92% - 59.93%	-0.06%
Temp loss from 59.93% - 63.80%	-0.12%	Energy loss from 59.93% - 63.80%	-0.27%
Heat source Y		**Heat source Y**	
Temp loss from 50.2% - 54.92%	0.16%	Energy loss from 50.2% - 54.92%	0.28%
Temp loss from 54.92% - 59.93%	-0.46%	Energy loss from 54.92% - 59.93%	-0.81%
Temp loss from 59.93% - 63.80%	-0.93%	Energy loss from 59.93% - 63.80%	-1.63%

Table 6.5 represents the percentages of transfer in temperature as well as energy when the air temperature remained constant and the relative humidity was increased for both heat source X and heat source Y. The measured percentage of temperature loss calculated between relative humidity settings is 0.02% with a gain of 0.12% for heat source X, and 0.16% loss and 0.93% gain for heat source Y. This indicating that heat source Y, similar to convection and changing air temperature, loses and gains more of its measured temperature expressed as a percentage when exposed to the same air temperature and relative humidity as heat source X. With an increase in relative humidity from 50.2% to 54.92%, both the heat source’s measured temperature decreases with a rise in relative humidity, while the surrounding air temperature remains fairly constant. With a further

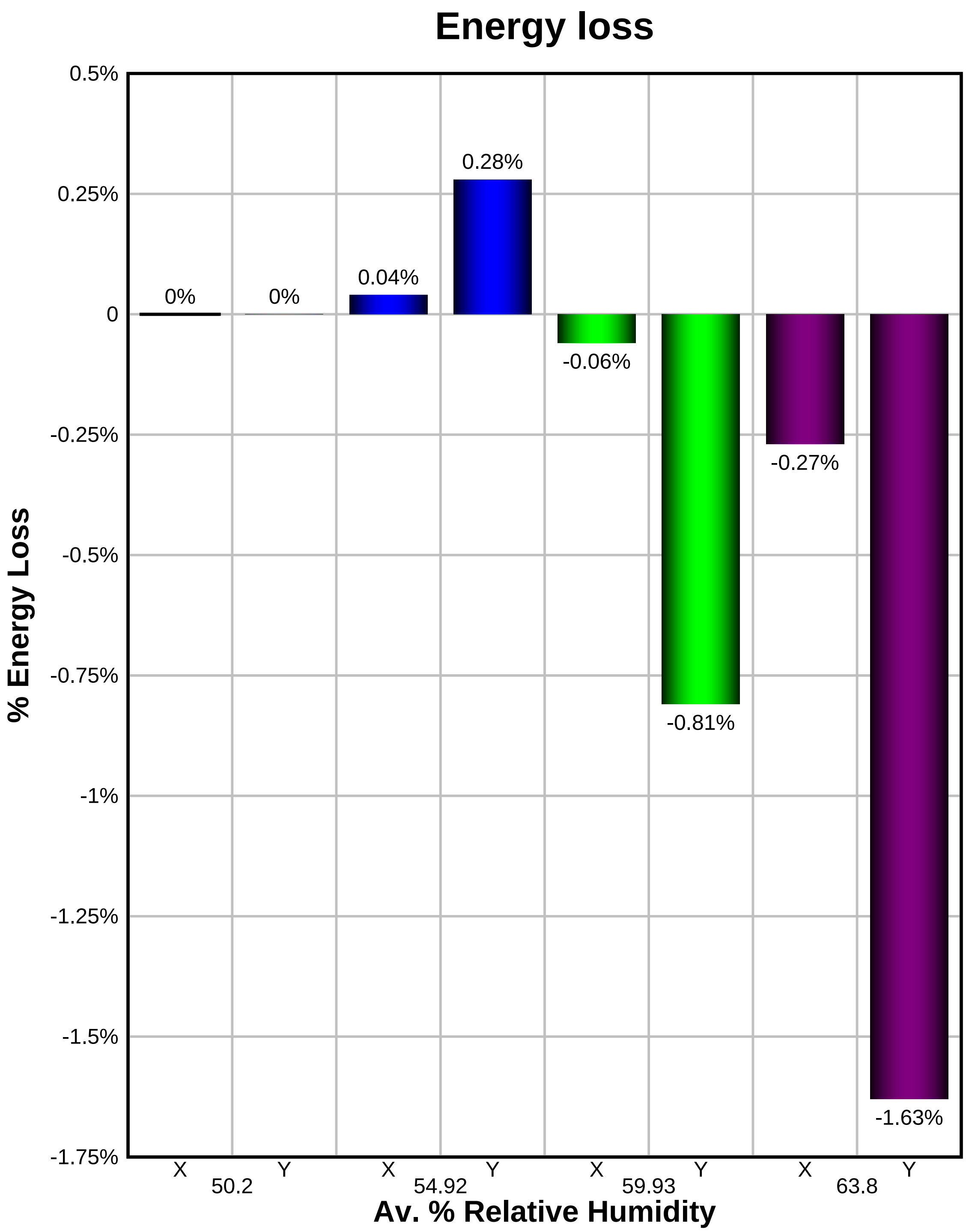
increase in relative humidity from 54.92% to 59.93% and again to 63.80%, a reversal of the energy transfer took place. Instead of the heat sources losing energy to the surrounding air, the surrounding air lost some of its energy to the heat sources. These results can be seen in graph 6.9.



Graph 6.9 Summarized percentages of measured temperature loss/gain

The two bars, of similar colour, each represent heat source X and heat source Y. The first bar of a particular colour represents heat source X and the second heat source Y. The results of both heat source X and heat source Y are represented on the same graph; this is to emphasize the importance of the heat source temperature when setting severity criteria.

When calculating the energy loss, heat source X lost 0.04% and gained 0.27% and heat source Y lost 0.28% and gained 1.63% of its energy within the experimented air temperature and relative humidity ranges. These results can be seen in graph 6.10.



Graph 6.10 Summarized percentages of heat energy loss/gain

The two bars, of similar colour, each represent heat source X and heat source Y. The first bar of a particular colour represents heat source X and the second heat source Y. The results of both heat source X and heat source Y are represented on the same graph; this is to emphasize the importance of the heat source temperature when setting severity criteria.

The second law of thermodynamics asserts that, in a closed system, the net flow of heat energy is always from warmer to cooler regions, unless work is done to move it in the other direction. In this experiment the mechanism is radiation, from the heat source to the surrounding air. The amount of energy radiated by the heat source can be calculated using equation 3.10,

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A T^4 \tag{3.10}$$

The amount of energy loss/gain to the surroundings can be calculated with

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A \left(T_1^4 - T_2^4\right) \tag{3.11}$$

Subtracting the radiated energy of heat source X at 25.25°C, RH 54.92%, from that at 25.34°C, RH 50.20%, reveals an energy transfer from heat source X to the surrounding air of 0.88W. This means that heat source X has lost 0.88W of its energy to the surroundings when the air temperature and relative humidity changed from 25.34°C, RH 50.20%, to 25.25°C, RH 54.92%, during the tested period.

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \text{ x} 10^{-8})(0.177)(676.3)^4$$

= 2 057.21W (energy of heat source X radiated at 25.34°C, RH 50.20%)

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \text{ x} 10^{-8})(0.177)(676.23)^4$$

= 2 056.33W (energy of heat source X radiated at 25.25°C, RH 54.92%)

Thus, Total energy transfer = 2 057.21 – 2 056.21

= 0.88W

If we use equation 3.11 with T_1 as the measured heat source temperature at 25.34°C, RH 50.20% and T_2 air temperature of 25.25°C, RH 54.92%, we find that the heat source is supposed to radiate 1 979.33W of its energy at an air temperature of 25.25°C, RH 54.92%, if there was no energy transfer present. The air will have energy of 1 978.52W at 25.25°C, RH 54.92%, calculated with equation 3.10. By subtracting the energy of the surrounding air from the energy the heat source is supposed to radiate at 25.25°C, RH 54.92%, we get a difference of 0.81W.

$$\frac{\Delta Q}{\Delta t} = (0.98)(5.67 \text{ x} 10^{-8})(0.177)((676.23)^4 - (298.25)^4)$$

$$= 1\ 978.52\text{W}$$

Thus $= 1\ 979.33 - 1\ 978.52$

$$= 0.81\text{W}$$

The above formula proves the existence of energy transfer between a heated object and the surrounding air. This transfer is very small when the air temperature remains the same while the relative humidity changes. Equation 3.10 can also be used to calculate the temperature and energy gain with an increase in relative humidity from 54.92% to 59.93% and again to 63.80%.

Chapter 7

Conclusions

7.1 Thermal Imager Tests

It is considered important, when undertaking thermal inspections, to know the operational aspects of the equipment, as well as the limitations when performing a specific task. Ensuring that the equipment is within the manufacturers specifications is just as important as correct interpretation and analysis of the thermal image. A calibration test or performance tests, as in the case of this study, can be performed to test the imager's accuracy against that of the manufacturers data sheet. From the thermal imager tests the user would be able to establish what the limitations of the thermal imager are. This will enable the thermographer to ensure that the hotspot object size is larger than the IFOVmeas. More accurate readings would also be achieved if the unit is within the manufacturers pre-tested settings. Any deviation will be an indication that the imager is due for calibration by an authorized calibration laboratory.

Knowing how the unit will react in different scenarios, like thermal flooding, will assist the thermographer to correctly interpret the findings. This will result in more reliable and credible reporting and severity criteria. The thermal imager is only a tool to assist the thermographer to "see" what cannot be seen with the naked eye. It is thus important that the thermographer undergoes the correct training and has some knowledge of the equipment to be tested. All of this, combined with the ability to read and understand heat patterns, will produce reasonable results and accurate severity criteria.

7.2. Experiment 1: Effect of wind (convection) on a heat source

Temperature is a measure of the average kinetic energy of molecular motion, whereas heat is a measure of the total kinetic energy (energy of movement) of molecular motion [25, p. 1]. These two definitions should be known and fully understood. When reporting on thermal images taken of a hotspot, the difference between temperature and energy is often wrongly categorized.

7.2.1 Radiated energy

Table 6.1 indicates the summarized results obtained during this experiment. Heat source Y lost a greater percentage of its start-off temperature while heat source X lost more °C per wind speed. The rate of heat transfer is dependent on the temperature difference between two objects. During this experiment the two objects were the wind temperature and the heat source. Heat source Y, with a start-off temperature of 248°C, loses between 2.6% and 8.3% more of its temperature than heat source X, with a start-off temperature of 496°C, when exposed to the same wind conditions over the same time period. The rate the temperature of the heat source changes is proportional to the rate the heat is transferred. A higher wind speed will transfer more heat away from the heated object. This is caused because less energy is available at the lower heat source temperature as than at the higher heat source temperature. The rate at which an object radiates energy is proportional to the fourth power of the Kelvin temperature scale. A body at 2000K radiates energy at a rate of $2^4 = 16$ times greater than one at 1000K [23]. Less energy means less resistance to retaining to its temperature.

Heat source X loses 28.5% of its initial measured temperature with a wind close to 30km/h and heat source Y loses 35.3%, proving that hotspots with a lower temperature (lower radiated energy) are more susceptible to convection than hotspots with a larger temperature (higher radiated energy), can result in one overlooking a problem or misinterpreting the severity of the problem, especially in the early stages, which could end catastrophically.

7.2.2 Heat energy and temperature

When considering the heat energy loss, the measured temperature of the two heat sources do not affect the energy loss when exposed to the same wind conditions for the same time period. Roughly the same percentage of energy was lost irrespective of the hotspot temperature. While wind close to 30km/h reduced the temperature of heat source X by 28.5% over the tested period, it lost 55.7% of its heat energy during the same time period than did heat source Y, which lost 35.3% of its temperature and 52.4% of its energy. The inverse is thus true for energy loss as opposed to temperature loss. The more energy a heat source has, the more it is willing to lose it to the environment due to convection. This is also in accordance to the second law of thermodynamics, in that the law states that heat flows from a hot object to a cold object; heat will not flow spontaneously from a colder object to a hotter object [7, p. 516].

It is very important to determine beforehand whether the temperature reading or the energy would be used for reporting. Knowing that there is a reduction in the measured temperature with wind present will assist in determining the accurate severity of the problem. The results obtained proves that a hotspot exposed close to a 30km/h wind for 10 minutes reduces the hotspot measured temperature by nearly 30%, depending on its temperature, while it loses more than 50% of its heat energy during the same time period, irrespective of its temperature. Convective cooling might be more severe taken that in nature wind does not only blow for 10 minutes at a time, as the case was during the experiment, and it is usually not steady but in gusts. Continuous wind will cool an object until it reaches equilibrium and no heat energy transfer takes place from the object to the moving air molecules.

This study serves to prove that convection does play a role when investigating hotspots in windy conditions, whether one works with measured temperature or heat energy. With measured temperature the heat source temperature influences the percentage temperature loss between 2.6% and 8.3%, whereas with heat energy the difference between the higher temperature heat source and the lower temperature heat source is very small, between 3% and 4%. The time which a heated object is exposed to windy conditions determines the percentage of temperature and energy loss, as well as the height above ground, due to altitude resulting in increased wind speed. Because of a combination of various factors that manipulate the temperature readings as well as airflow around the heated object, that were not considered during this study, the results of this study cannot be used to formulate a correction factor for wind but can only serve as an indication of the behaviour of heated objects in windy conditions. Taking the above-mentioned results and knowledge of temperature behaviour in windy conditions into account next time a thermal survey is done in windy conditions, will add more credibility to the reported results.

7.2.3 Experiment 1: Scope for future work

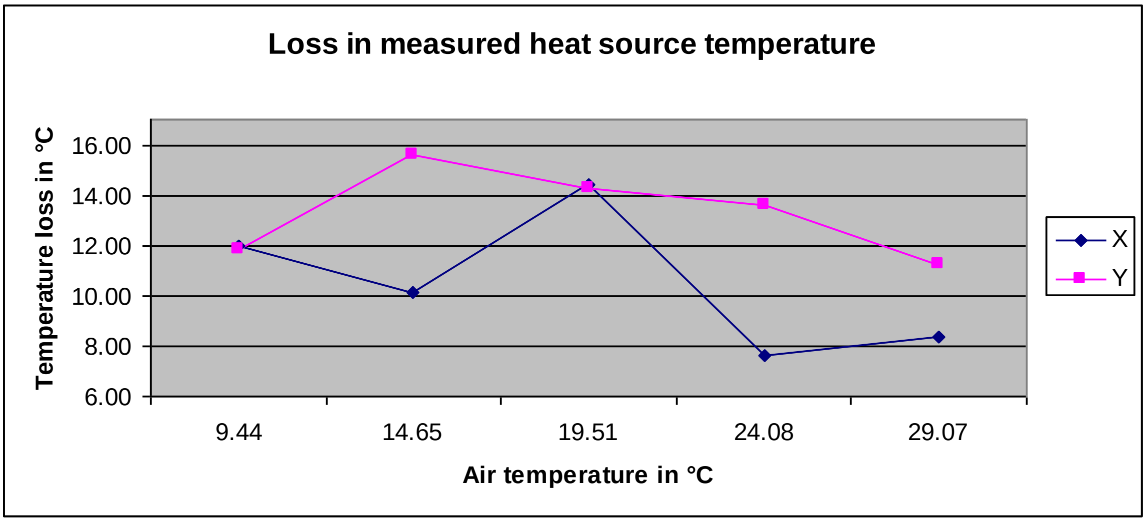
Additional tests should be conducted to determine the threshold (equilibrium) of a pre-determined hotspot temperature exposed to a pre-determined wind speed. Smaller wind speed intervals will give more detail regarding the rate of temperature loss relative to the wind speed. This will enable the thermographer to better understand the temperature behaviour of equipment under certain wind conditions and duration.

More advanced tests can be done to determine whether the same results would be obtained when performed on different equipment types found inside a substation under the same wind conditions for the same time period. This can be obtained by simulating fault conditions, e.g. a loose clamp connector, on various items of equipment at a certified HV test laboratory. Simulating the same fault current through various items of equipment will theoretically radiate the same temperature, given that all the equipment is made from the same material. The shape and orientation of the equipment will also influence the airflow around the equipment that will result in different cooling patterns. It is therefore advisable also to investigate this phenomenon during the same test.

7.3. Experiment 2: Effect of air temperature on a heat source

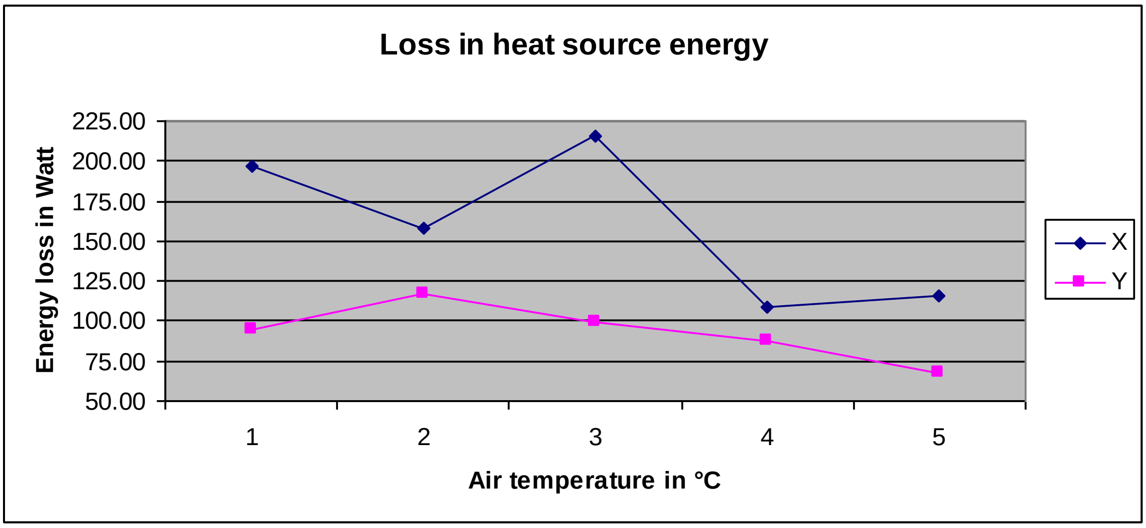
The rate of heat transfer is dependent on the temperature difference between two objects. During this experiment the objects were the heat source and the surrounding air inside the climate controlled cabinet. This means that the rate of heat transfer will change with a change in any of the two temperature measurements. When the air temperature inside the cabinet was increased, the measured temperatures of the heat sources both decreased. This is due to the energy transfer between the surrounding air and the heated object. The first law of thermodynamics states, that in a closed system, the energy entering the system equals the energy leaving the system [7, p. 516]. The increased energy of the surrounding air must be transferred from somewhere, and the somewhere in the case of this experiment is the heat source.

At low ambient air temperatures, a higher radiated heat source temperature was measured for both heat source X and heat source Y than at higher air temperatures. This can be seen from table 6.2 in chapter 6. When the air temperature was increased and the system was near equilibrium, the rate at which the heat source measured temperature decreased was supposed to get progressively lower. This was not entirely the case during the experiment. This is due to various factors such as: no radiometric temperature measurements were taken of the heat sources, and the thermal images were taken before the thermostat was fully switched on and heated the heat source to its set value. Although the influence is small, it leads to results that are not absolutely in accordance with the laws of thermodynamics. Graph 7.1 illustrates the loss in measured heat source temperatures for heat source X and heat source Y while the air temperature was increased.



Graph 7.1 Temperature loss of heat source X and Y at various air temperatures

In table 6.2 in chapter 6 the energy loss from the previous temperature reading is in accordance with the fact that hotter objects have a greater tendency to transfer heat. The lower the temperature of an object is, the greater the tendency of that object to be on the receiving end of the heat transfer. The energy loss of heat source X is higher than the energy loss of heat source Y at all temperature readings. This is illustrated in graph 7.2.



Graph 7.2 Energy loss of heat source X and Y at various air temperatures

The percentage of temperature loss of the heat source shows a slight decrease with the increase in air temperature. This is due to the higher energy of the higher air temperature that results in less energy transfer between the hot object and the surrounding air, thus proving the hypothesis on the temperature transfer from a hotspot to the surrounding air; more temperature and energy loss occurs at lower surrounding air temperatures due to the law of conservation of energy. The fact that the heat source has less energy at lower temperatures than at hotter temperatures, means that it is more likely to transfer energy to its surroundings, also known as thermal inertia.

The results obtained in this experiment prove both the first and second law of thermodynamics and that both the hotspot temperature and the air temperature should be taken into account when doing thermal inspections. A hotspot measured in lower air temperatures would stand out to be more severe than one with the same temperature at higher air temperatures. Lower hotspot temperatures would also be influenced much more easily by the air temperatures than hotter hotspots.

These experiments were conducted in near ideal conditions. In nature not only one but a combination, for example, convection, air temperature, relative humidity, solar loading and a varying load, influence the severity of a hotspot. Because of this it is impossible to formulate a correction factor from the results in this study. For a themographer is it important to know to which extent each of these factors influences the reading. It is then left to the experience and discretion of the thermographer to categorize the severity of a problem according to the atmospheric condition.

7.3.1 Experiment 2: Scope for future work

Additional tests should be conducted to determine the effect of smaller temperature intervals. Thermocouples should also be connected to the heat source ensuring accurate radiometric temperature readings of the heat source temperature. These tests can also include different relative humidity settings and wind. The experiments in this study were done under controlled conditions and the results obtained should be tested in a natural environment in which all the climatic elements exist, and at the same time have a combined effect on a hotspot.

7.4. Experiment 3: Effect of relative humidity on a heat source

Relative humidity is dependent on the air temperatures. Higher air temperatures result in the increase in the kinetic energy of molecules, increasing the rate of evaporation. This happens in nature on a daily basis. Mornings with low air temperatures have less energy resulting in a high relative humidity, while warmer afternoons have more energy resulting in a lower relative humidity.

During the experiment the air temperature was kept constant, therefore the energy of the air was also constant. The change in relative humidity was achieved by changing the amount of moisture in the air. The energy transfer with a fluctuating relative humidity is very small as is the influence on the measured temperature of a hotspot. This can be seen from graph 6.9 in chapter 6. Similar to changing air temperature at constant relative humidity, lower temperature hotspots are more easily influenced by constant air temperature at changing relative humidity.

From 55% relative humidity both heat sources gained temperature and energy from the surrounding air instead of losing it. This is due to the attracting forces getting too strong between the water vapour present in the air and the heat source, condensation. Very small amounts of water vapour hit the surface of the heat source, exchanging energy from the surrounding air mass to the surface of the heat source, thus increasing the energy of the heat source. The smallest energy addition at low heat source temperatures will bring about a higher percentage increase in the results than will higher heat source temperatures. On a small scale during the experiment two processes occurred simultaneously: evaporation and condensation.

7.4.1 Experiment 3: Scope for future work

Additional tests should be conducted to determine the effect at relative humidity lower than 50% and higher than 65%. These tests can also include different temperature settings. This will indicate if hotspots react differently when exposed to different temperature settings, but to the same relative humidity. Thermocouples should also be connected to the heat source ensuring accurate radiometric temperature readings of the heat source temperature.

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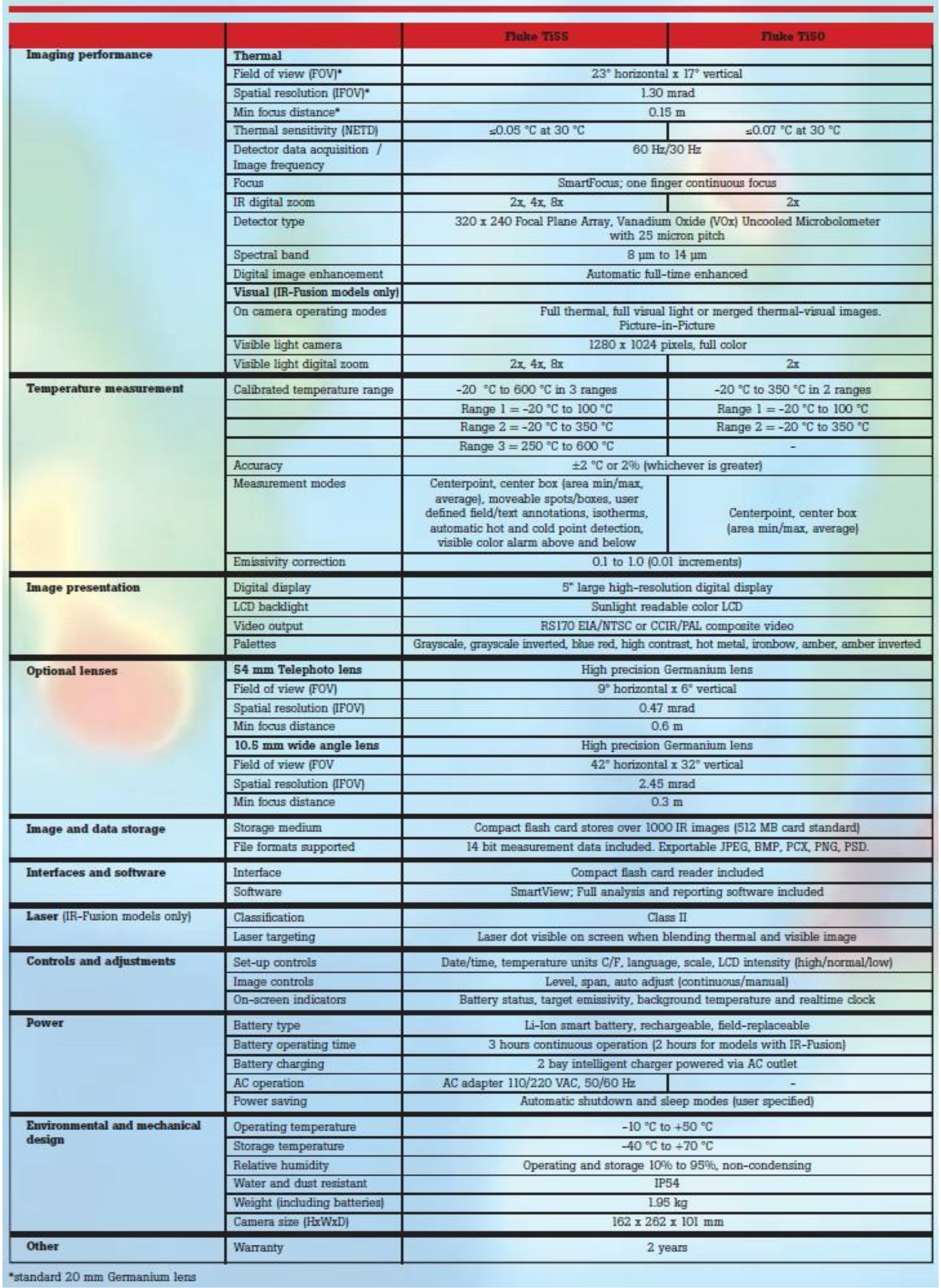
Annexure

Annexure A: Data sheet for Fluke Ti55 & Ti50 Thermal imager



		Fluke Ti55	Fluke Ti50
Imaging performance	**Thermal**		
	Field of view (FOV)*	23° horizontal x 17° vertical	
	Spatial resolution (IFOV)*	1.30 mrad	
	Min focus distance*	0.15 m	
	Thermal sensitivity (NETD)	≤0.05 °C at 30 °C	≤0.07 °C at 30 °C
	Detector data acquisition / Image frequency	60 Hz/30 Hz	
	Focus	SmartFocus; one finger continuous focus	
	IR digital zoom	2x, 4x, 8x	2x
	Detector type	320 x 240 Focal Plane Array, Vanadium Oxide (VOx) Uncooled Microbolometer with 25 micron pitch	
	Spectral band	8 µm to 14 µm	
	Digital image enhancement	Automatic full-time enhanced	
	Visual (IR-Fusion models only)		
	On camera operating modes	Full thermal, full visual light or merged thermal-visual images. Picture-in-Picture	
	Visible light camera	1280 x 1024 pixels, full color	
	Visible light digital zoom	2x, 4x, 8x	2x
Temperature measurement	Calibrated temperature range	-20 °C to 600 °C in 3 ranges	-20 °C to 350 °C in 2 ranges
		Range 1 = -20 °C to 100 °C	Range 1 = -20 °C to 100 °C
		Range 2 = -20 °C to 350 °C	Range 2 = -20 °C to 350 °C
		Range 3 = 250 °C to 600 °C	-
	Accuracy	±2 °C or 2% (whichever is greater)	
	Measurement modes	Centerpoint, center box (area min/max, average), moveable spots/boxes, user defined field/text annotations, isotherms, automatic hot and cold point detection, visible color alarm above and below	Centerpoint, center box (area min/max, average)
	Emissivity correction	0.1 to 1.0 (0.01 increments)	
Image presentation	Digital display	5" large high-resolution digital display	
	LCD backlight	Sunlight readable color LCD	
	Video output	RS170 EIA/NTSC or CCIR/PAL composite video	
	Palettes	Grayscale, grayscale inverted, blue red, high contrast, hot metal, ironbow, amber, amber inverted	
Optional lenses	**54 mm Telephoto lens**	High precision Germanium lens	
	Field of view (FOV)	9° horizontal x 6° vertical	
	Spatial resolution (IFOV)	0.47 mrad	
	Min focus distance	0.6 m	
	10.5 mm wide angle lens	High precision Germanium lens	
	Field of view (FOV	42° horizontal x 32° vertical	
	Spatial resolution (IFOV)	2.45 mrad	
	Min focus distance	0.3 m	
Image and data storage	Storage medium	Compact flash card stores over 1000 IR images (512 MB card standard)	
	File formats supported	14 bit measurement data included. Exportable JPEG, BMP, PCX, PNG, PSD.	
Interfaces and software	Interface	Compact flash card reader included	
	Software	SmartView; Full analysis and reporting software included	
Laser (IR-Fusion models only)	Classification	Class II	
	Laser targeting	Laser dot visible on screen when blending thermal and visible image	
Controls and adjustments	Set-up controls	Date/time, temperature units C/F, language, scale, LCD intensity (high/normal/low)	
	Image controls	Level, span, auto adjust (continuous/manual)	
	On-screen indicators	Battery status, target emissivity, background temperature and realtime clock	
Power	Battery type	Li-Ion smart battery, rechargeable, field-replaceable	
	Battery operating time	3 hours continuous operation (2 hours for models with IR-Fusion)	
	Battery charging	2 bay intelligent charger powered via AC outlet	
	AC operation	AC adapter 110/220 VAC, 50/60 Hz	-
	Power saving	Automatic shutdown and sleep modes (user specified)	
Environmental and mechanical design	Operating temperature	-10 °C to +50 °C	
	Storage temperature	-40 °C to +70 °C	
	Relative humidity	Operating and storage 10% to 95%, non-condensing	
	Water and dust resistant	IP54	
	Weight (including batteries)	1.95 kg	
	Camera size (HxWxD)	162 x 262 x 101 mm	
Other	Warranty	2 years	

*standard 20 mm Germanium lens